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Prepared in cooperation with the
Glen Canyon Dam Adaptive
Management Program

Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2015–2017

Prepared by
Bureau of Reclamation
Upper Colorado Regional Office
and
U.S. Geological Survey
Grand Canyon Monitoring and
Research Center

Planning Document
Draft: August 1, 2014

U.S. Department of the Interior
U.S. Geological Survey

Cover: View of Colorado River from Nankoweap Trail in Marble Canyon, Grand Canyon National Park, Scott VanderKooi, U.S. Geolgoical Survery.

RECLAMATION
Managing Water in the West

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Prepared by

Bureau of Reclamation
Upper Colorado Regional Office
Salt Lake City, Utah

and

U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center
Flagstaff, Arizona

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Chapter 1. Bureau of Reclamation, Glen Canyon Dam Adaptive Management Program, Triennial Budget and Work Plan—Fiscal Years 2015–17

Introduction

The Glen Canyon Dam Adaptive Management Program (GCDAMP) is a science-based process for continually improving management practices related to the operation of Glen Canyon Dam (GCD) by emphasizing learning through monitoring, research, and experimentation, in fulfillment of the consultation and research commitments of the Grand Canyon Protection Act (GCPA). The Bureau of Reclamation's (BOR) Upper Colorado Region (BRUC) is responsible for administering funds for the GCDAMP and providing those funds for monitoring, research, and stakeholder involvement. The majority of program funding is derived from hydropower revenues; however, supplemental funding is provided by various Department of the Interior (DOI) agencies that receive appropriations. These agencies include BOR, the U.S. Geological Survey (USGS), the National Park Service (NPS), the U.S. Fish and Wildlife Service (USFWS), and the Bureau of Indian Affairs (BIA).

The budget and work plan for fiscal years (FY) 2015–17 was developed on the basis of previous budgets and work plans, the GCDAMP Biennial Budget and Work Process approved by the AMWG on May 6, 2010, the Streamlined GCMRC Biennial Work Planning Process, version April 3, 2011, and the May 7, 2014 memorandum from Assistant Secretary and Secretary's Designee Anne Castle on development of a tiennial GCDAMP Budget and Work Plan. Additional consideration was given to meeting the commitments outlined in the following compliance documents (1) the *2007 USFWS Biological Opinion for the Proposed Adoption of Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (2007 Opinion); (2) the *2011 Reclamation Environmental Assessment* (EA) and *2012 Finding of No Significant Impact* (FONSI) *for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020* (HFE Protocol); (3) the *2011 Reclamation EA and 2012 FONSI for Non-native Fish Control Downstream from Glen Canyon Dam* (NNFC EA and FONSI); and the *2011 USFWS Final Biological Opinion on the Operation of Glen Canyon Dam including High Flow Experiments and Non-Native Fish Control* (2011 Opinion). Additionally, this budget and work plan was developed in consideration of the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS).

The process used to arrive at the FY15–17 budget and work plan was adopted by the AMWG in 2004 and revised in 2010 to a 2-year fixed budget process, and subsequently revised to a triennial budget process by the GCDAMP Secretary's Designee on May 7, 2014. The Budget Ad Hoc Group (BAHG) of the Technical Work Group (TWG), with input from the Cultural Resources Ad Hoc Group (CRAHG), worked with the BRUC and GCMRC to develop a proposal for the TWG. The TWG then reviews the proposed budget and work plan and develops a recommendation to the AMWG.

The FY15–17 budget and work plan was also prepared in consideration of the projected hydrograph for Lake Powell release for water year (WY) 2015, which is based on forecasted inflows to Lake Powell and GCD releases determined by the 1996 Record of Decision on the operation of Glen Canyon Dam and the 2007 Record of Decision on Interim Guidelines for Coordinated Operation of Lake Mead and Lake Powell. It also observes commitments made in the 2007 and 2011 U.S. Fish and Wildlife biological opinions. The projected hydrograph is based on best estimates available from BOR's 24-month study released in May 2014, however, the forecast is subject to change as further data becomes available.

A.1. Adaptive Management Work Group Costs

This budget represents BOR staff costs to perform the daily activities required to support the Adaptive Management Work Group (AMWG), the GCDAMP Federal Advisory Committee Act (FACA) committee. The work includes completing assignments resulting from AMWG meetings, consulting with stakeholders on a variety of GCDAMP issues relating to the operation of GCD, disseminating pertinent information to the AMWG, preparing and tracking budget expenses, and updating BOR's Web page. BOR also responds to regular requests from the General Services Administration (GSA) to complete FACA reports and incorporate meeting and member information into the FACA database. BOR is now required to complete all stakeholder travel, activities that range from preparing travel authorizations to completing travel vouchers.

The primary goal is to perform all work associated with the AMWG in a timely and efficient manner, while using the funds available as prudently as possible. Secondary goals include increasing each stakeholder's awareness of significant budget and legislative issues related to the GCDAMP, improving working relationships with the AMWG members/alternates, finding constructive ways to resolve differences, and addressing individual concerns in an open and accepting forum of discussion.

BOR will work to ensure that personnel costs will not exceed what has been proposed in the budget unless Federal employee salaries are increased above the consumer price index (CPI). BOR staff will provide budget information to the AMWG on a regular basis. Completed work products will be of high quality and promptly distributed to AMWG members/alternates and interested parties. Budget reports will be presented in a format conducive to AMWG needs.

Budget FY15 = $196,530 FY16 = $202,425 FY17 = $208,498

Reclamation Project - Personnel Costs—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	134,443	136,846	141,030	141,337	145,578	149,944	154,443
Subtotal	134,443	136,846	141,030	141,337	145,578	149,944	154,443
DOI Overhead (35%)	44,367	47,923	49,361	49,468	50,952	52,481	54,055
Project total	178,810	184,846	190,391	190,805	196,530	202,425	208,498
Total outsourced (%)							

A.2. AMWG Member Travel Reimbursement

This budget covers the costs to reimburse AMWG members or alternates to attend regularly scheduled AMWG meetings.

Reimbursing AMWG members or alternates for travel expenses is done to encourage their attendance at all meetings. Many members live outside of Phoenix, Arizona, where meetings are often held. As a result, many members must incur travel costs. Having BOR provide reimbursement to AMWG members or alternates for air travel or mileage for the use of private vehicles, as well as other related travel costs such as hotel, per diem, and rental car increases opportunities for members to participate in a variety of AMWG assignments. Because BOR can purchase airline tickets at the Federal Government rate, there are additional cost savings to the program.

The GCDAMP benefits from having all AMWG members participating in regularly scheduled meetings. As a collective body, they address and resolve concerns associated with the operation of GCD and make recommendations to the Secretary of the Interior for continued science efforts performed below the GCD.

Budget FY15 = $15,689 FY16 = $16, 159 FY17 = $16,644

Reclamation Project - AMWG Travel Reimbursement—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	17,671	14,756	15,199	15,232	15,689	16,159	16,644
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	17,671	14,756	15,199	15,232	15,689	16,159	16,644
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	17,671	14,756	15,199	15,232	15,689	16,159	16,644
Total outsourced (%)	—	—	—	——	—	—	—

A.3. AMWG Reclamation Travel

This budget supports travel expenses BOR staff incur to attend AMWG and ad hoc group meetings. The primary goal is for BOR staff to be able to travel to meetings and participate in completing AMWG/TWG assignments. By doing so, the program benefits from greater interaction between BOR staff and GCDAMP members, and opportunities for BOR staff to obtain the latest results from monitoring and research being conducted by the GCDAMP.

BOR staff will be involved with AMWG/TWG members in completing work assignments and resolving issues that affect the GCDAMP. They will develop better working relationships with all involved and work toward consensus with AMWG members on a variety of issues.

Budget FY15 = $16,097 FY16 = $16,580 FY17 = $17,077

Reclamation Project - Reclamation Travel—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	14,344	15,140	15,595	15,628	16,097	16,580	17,077
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	14,344	15,140	15,595	15,628	16,097	16,580	17,077
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	14,344	15,140	15,595	15,628	16,097	16,580	17,077
Total outsourced (%)	—	—	—	—	—	—	—

A.4. AMWG Facilitation Contract

This budget supports a facilitator who is under contract to BOR to provide facilitations services for AMWG meetings. This person may also assist AMWG ad hoc groups in completing assignments.

The facilitator's primary responsibility is to keep the AMWG meetings organized and help the members reach consensus on important issues. The facilitator will create an atmosphere in which the members and other participants at AMWG meetings feel comfortable expressing their individual viewpoints.

Budget FY15 = $79,556 FY16 = $81,943 FY17 = $84,401

Reclamation Project - Facilitation Contract—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	27,274	40,531	41,747	0	79,556	81,943	84,401
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	27,274	40,531	41,747	0	79,556	81,943	84,401
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	27,274	40,531	41,747	0	79,556	81,943	84,401
Total outsourced (%)	—	—	—	—	—	—	—

A.5. Public Outreach

This budget covers the expenses for BOR staff and the Public Outreach Ad Hoc Group (POAHG) to develop materials for the GCDAMP public outreach efforts.

BOR public affairs staff and the POAHG will work jointly in developing materials to inform and educate the public on the goals and administration of the GCDAMP. They will keep other GCDAMP members advised of progress and expenditures.

Products will include fact sheets, Web site information, tribal outreach materials, video B-roll, special events, conference participation, and other pertinent means of advising the public and program members on the achievements of the GCDAMP. The POAHG will maintain accurate records of payments made against the contracts and will keep BOR staff informed of discrepancies or concerns.

Since 2010, this line item has accumulated approximately $100,000 in carryover funding as a result of reduced activity. Part of the proposal for the FY15–17 triennial budget is to use $50,000 of these funds each in FY15 and FY16 to implement the Glen Canyon Dam Administrative History Pilot Project. This project would help accomplish the goals of the Public Outreach Ad Hoc Group by providing a better understanding of the history of the GCDAMP, its work, and participants. The pilot project will undertake the following:

- Begin developing oral histories and interviews with AMP historical figures
- Create an annotated bibliography for program related literature
- Create a website and library database for information archival and retrieval
- Create a chronological program overview including participants
- Develop a new participant's handbook for the AMP.

Budget FY15 = $63,054 FY16 = $64,945 FY17 = $66,893

Admin. History (carryover)

FY15 = $50,000 FY16 = $50,000 FY17 = $0

Reclamation Project - Public Outreach—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Operations/supplies	2,500	2,500	2,500	2,500	2,500	2,500	2,500
Reclamation salaries	38,284	40,596	41,914	43,272	43,373	44,774	46,217
Subtotal	42,784	45,096	46,414	47,772	47,873	49,274	50,771
DOI Overhead (35%)	13,400	14,209	14,670	15,145	15,181	15,671	16,176
Project total	56,184	59,305	61,084	62,917	63,054	64,945	66,893
Total outsourced (%)	—	—	—	—	—	—	—

A.6. AMWG Other

This budget represents some of the other “miscellaneous” expenses incurred in operation of the AMWG, including the following expenses:

- Overnight mailings of AMWG meeting packets
- Copying of reports
- Purchasing meeting materials (cassette tapes, markers, paper, software upgrades for GCDAMP Web site posting, etc.)
- Purchasing equipment (audio recording/transcribing machines).

In addition to the expenses noted above, training courses are often required for staff to keep current on environmental issues, FACA changes, computer technology improvements, etc. The primary goal is to limit spending on “other” items as much as possible. By doing so, more money can be applied to science and research. Other expenses will be kept to a minimum in an effort to reduce the administrative portion of the GCDAMP budget.

Budget FY15 = $9,047 FY16 = $9,318 FY17 = $9,598

Reclamation Project - Other—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	6,062	6,509	6,783	7,028	7,047	7,318	7,598
Operations/supplies	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	8,062	8,509	8,783	9,028	9,047	9,318	9,598
DOI Overhead (35%)	—	—	—	—			
Project total	8,062	8,509	8,783	9,028	9,047	9,318	9,598
Total outsourced (%)	—	—	—	—	—	—	—

B.1. TWG Costs

This budget represents BOR staff costs to perform the daily activities required to support the TWG, a subgroup of the AMWG. The work includes completing assignments resulting from TWG meetings, consulting with stakeholders on a variety of GCDAMP issues relating to the operation of GCD, disseminating pertinent information to TWG members, preparing and tracking budget expenses, and updating the Web pages BOR maintains for the program. BOR also completes all stakeholder travel activities, which range from preparing travel authorizations to completing travel vouchers.

Personnel costs will not exceed what has been proposed in the budget unless Federal employee salaries are increased above the CPI. BOR staff will provide budget information to the TWG on a regular basis. Completed work products will be promptly distributed to TWG members/alternates and interested parties.

Budget FY15 = $97,863 FY16 = $100,799 FY17 = $103,823

Reclamation Project - Personnel Costs—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	64,593	68,181	70,227	70,380	72,491	74,666	76,906
Subtotal	64,593	68,181	70,227	70,380	72,491	74,666	76,906
DOI Overhead (35%)	22,608	23,864	24,579	24,633	25,372	26,133	26,917
Project total	87,201	92,045	94,806	95,013	97,863	100,799	103,823
Total outsourced (%)	—	—	—	—	—	—	—

B.2. TWG Member Travel Reimbursement

This budget provides funds to reimburse TWG members or alternates for expenses incurred to attend regularly scheduled TWG meetings.

Reimbursing TWG members or alternates for travel expenses is done to encourage their attendance at all meetings. By providing reimbursement to TWG members or alternates for air travel or mileage for the use of private vehicles, as well as other related travel costs such as hotel, per diem, and rental car increases opportunities for members to participate in a variety of TWG assignments. Because BOR can purchase airline tickets at the Federal Government rate, there are additional cost savings to the program.

The GCDAMP will benefit from having all the TWG members participate in regularly scheduled meetings. As a collective body, TWG members address and resolve concerns associated with the operation of GCD and make recommendations to the AMWG for continued research.

Budget FY15 = $23,051 FY16 = $23,743 FY17 = $24,455

Reclamation Project - TWG Member Travel Reimbursement—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	24,232	21,861	22,331	22,380	23,051	23,743	24,455
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	24,232	21,861	22,331	22,380	23,051	23,743	24,455
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	24,232	21,861	22,331	22,380	23,051	23,743	24,455
Total outsourced (%)	—	—	—	—	—	—	—

B.3. TWG Reclamation Travel

This budget covers travel expenses that BOR staff will incur to prepare for and attend TWG meetings and ad hoc group meetings resulting from AMWG/TWG assignments. The primary goal is for BOR staff to be able to travel to meetings and participate in completing AMWG/TWG assignments. BOR staff will continue to be involved in meeting with AMWG/TWG members to complete work assignments and resolve issues that affect the operation of GCD. They will develop better working relationships with all involved and work toward consensus on a variety of GCDAMP issues.

Budget FY15 = $15,903 FY16 = $16,381 FY17 = $16,872

Reclamation Project - Reclamation Travel—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	17,864	14,958	15,407	15,440	15,903	16,381	16,872
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	17,864	14,958	15,407	15,440	15,903	16,381	16,872
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	17,864	14,958	15,407	15,440	15,903	16,381	16,872
Total outsourced (%)	—	—	—	—	—	—	—

B.4. TWG Chair Reimbursement/Facilitation

This budget supports a person who is under contract to BOR to serve as the chairperson for the TWG. This person may also assist AMWG/TWG ad hoc groups in completing assignments. In the event that the TWG chair salary is covered through funding outside the GCDAMP, these funds can be used by BOR for administrative purposes or to cover professional facilitation of TWG issues.

The chairperson's primary responsibility is to conduct regularly scheduled TWG meetings. The chairperson also participates in ad hoc group assignments and works closely with BOR and GCMRC staff in setting meeting agendas. The chairperson follows up on TWG and ad hoc group assignments and ensures that information is shared with the members and alternates in a timely manner.

The chairperson creates an atmosphere in which the members and other participants at TWG meetings feel comfortable expressing their individual viewpoints. The chairperson will bring the TWG members to consensus on sensitive issues with the ultimate goal of making recommendations to the AMWG that incorporate the best scientific information available to the GCDAMP. The chairperson will follow up on action items and make assignments as necessary to accomplish TWG objectives.

Part or all, of this budget may also be used to support a facilitator who is under contract to BOR to provide facilitations services for TWG meetings. This person may also assist TWG ad hoc groups in completing assignments. The facilitator will help keep the TWG meetings organized and help the members reach consensus on important issues. The facilitator will create an atmosphere in which the members and other participants at TWG meetings feel comfortable expressing their individual viewpoints.

In 2013, a solicitor review of the legal authority to expend federal monies to fund the TWG Chair was initiated. Pending the results of this review this budget item may be modified or eliminated.

Budget FY15 = $32,050 FY16 = $33,012 FY17 = $34,002

Reclamation Project - TWG Chair Reimbursement—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	24,913	30,145	31,049	31,117	32,050	33,012	34,002
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	24,913	30,145	31,049	31,980	32,050	33,012	34,002
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	24,913	30,145	31,049	31,980	32,050	33,012	34,002
Total outsourced (%)	—	—	—	—	—	—	—

B.5. TWG Other

This budget represents some of the other “miscellaneous” expenses incurred in support of the TWG, including the following expenses:

- Overnight mailings of TWG meeting packets
- Copying of reports
- Purchasing meeting materials (cassette tapes, markers, paper, etc.)
- Purchasing equipment (audio recording/transcribing machines)

The primary goal is to limit spending on “other” items as much as possible. By doing so, more money can be spent on science and research. Other expenses will be kept to a minimum in an effort to keep within the GCDAMP budget.

Budget FY15 = $2,585 FY16 = $2,662 FY17 = $2,742

Reclamation Project - Other—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	2,303	2,431	2,504	2,509	2,585	2,662	2,742
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	2,303	2,431	2,504	2,509	2,585	2,662	2,742
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	2,303	2,431	2,504	2,509	2,585	2,662	2,742
Total outsourced (%)	—	—	—	—	—	—	—

C.1. Administrative Support for NPS Permitting

This budget item provides funding to support the Grand Canyon National Park permitting of research and monitoring projects conducted under the GCDAMP. Grand Canyon National Park employs a permitting specialist and staff who review all proposals for projects to be completed in the park. The program provides these funds under the auspices of the GCDAMP to offset the park's administrative burden in providing permitting services. The primary goal is to ensure that projects conducted under the GCDAMP are reviewed and permitted by the NPS. Projects conducted under the GCDAMP will receive permits from the NPS in a timely manner.

Budget FY15 = $137,319 FY16 = $140,046 FY17 = $144,166

Reclamation Project - Administrative Support for NPS Permitting—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	120,240	121,882	126,242	125,811	129,586	133,743	137,478
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	120,240	121,882	126,242	147,318 *	137,319	140,046	144,166
Total outsourced (%)	—	—	—	—	—	—	—

* 2014 includes $17,297 cost reimbursement from FY12 & 13.

C.2. Contract Administration

This budget covers the expenses for BOR staff to prepare and monitor contracts associated with the GCDAMP. Specifically, these contracts are for AMWG facilitation, TWG chairperson reimbursement, Science Advisors, Tribal participation, Tribal resource monitoring, and programmatic agreement (PA) work.

BOR contract specialists will accurately apply funds spent on individual contracts to ensure costs do not exceed contract limits. They will keep other BOR staff informed as to those charges so accurate reporting can be made to both AMWG and TWG members.

Contract specialists will ensure that individual contractors are fulfilling the requirements of their contracts. They will maintain accurate records of payments made against the contracts and will keep BOR staff informed of discrepancies or concerns. Work will be completed on time and within the limits of the contract.

Budget FY15 = $45,362 FY16 = $46,723 FY17 = $48,124

Reclamation Project - Contract Administration—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	29,491	31,604	32,552	32,623	33,601	34,610	35,647
Subtotal	29,491	31,604	32,552	32,623	33,601	34,610	35,647
DOI Overhead (35%)	10,479	11,061	11,393	11,418	11,761	12,113	12,477
Project total	40,420	42,665	43,945	44,041	45,362	46,723	48,124
Total outsourced (%)	—	—	—	—	—	—	—

C.3. Science Advisor Contract

This budget provides funding to support Science Advisors for technical reviews and advisory services to the GCDAMP. The program provides these funds under the auspices of the GCDAMP to obtain objective independent review of documents and work plans, and provide decision support to participating agencies and stakeholders.

Budget FY15 = $75,000 FY16 = $77,250 FY17 = $79,568

Science Advisor Contract Oversight — Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor		—		—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal					75,000	77,250	79,568
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	—	—	—	—	75,000	77,250	79,568
Total outsourced (%)	—	—	—	—	—	—	—

C.4. Experimental Fund

This budget item reserves funds for conducting experiments under the GCDAMP. The funds will be available to conduct experiments when conditions are appropriate. If the funds are not needed in a given year, they will be transferred to the Native Fish Conservation Contingency Fund.

In 2015, $250,000 of the fund would be used to install acoustic flow meters on the jet tubes at Glen Canyon Dam. The HFE Protocol is a GCDAMP experiment and better instrumentation is required to adequately monitor HFEs. The project is further defined below in C.5. Installation of Acoustic Flow Meters in Glen Canyon Dam Bypass Tubes.

Budget FY15 = $286,815 FY16 = $552,920 FY17 = $569,507

Reclamation Project - Experimental Carryover Funds—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor		—		—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	505,838	521,013	515,000	521,180	$286,815	552,920	569,507
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	505,838	521,013	515,000	521,180	$286,815	552,920	569,507
Total outsourced (%)	—	—	—	—	—	—	—

C.5. Installation of Acoustic Flow Meters in Glen Canyon Dam Bypass Tubes

Reclamation needs an accurate measurement of releases through the four bypass tubes at Glen Canyon Dam. Releases from the bypass tubes are currently estimated from rating curves that relate the hollow jet valve opening percentages and reservoir water surface elevation to a flow through each bypass tube. Independent flow measurements of the river and water surface elevation measurements during recent use of the bypass tubes during the November 2013 High Flow Experiment (HFE) indicate that these rating curves likely underestimated the total bypass flow by about 12% (about 2,000 cfs). This resulted in a total bypass release of approximately 17,000 cfs and an average release rate of approximately 4,250 cfs from each bypass tube.

The error found in the rating curve estimate of the bypass tube release is a safety concern. The maximum safe release rate from each bypass tube is 3,750 cfs. This limit is based on limiting the velocity of water in the bypass tubes to prevent possible cavitation and resulting damage to the tubes. The water velocity when the bypass tubes are operated at the maximum recommended capacity is approximately 24 feet per second. During the November 2013 HFE, when outlet works releases were approximately 17,000 cfs, or 4,250 cfs for each bypass tube, the water velocity through the bypass tubes was approximately 27 feet per second, which potentially could have created cavitation damage within the bypass tubes, although there is no evidence damage has occurred from past use of the bypass tubes.

Accurate release measurements are also needed for accounting purposes to measure the total water released from Glen Canyon Dam. The 2007 Interim Guidelines, which govern the annual operations of Glen Canyon Dam, outline the required annual release volumes based on reservoir elevations. For HFE releases to utilize bypass tubes and be accurately accounted for as part of the required annual volumes, accurate measurements are required. Accurate release measurements are also needed to monitor the effects of HFEs. The ability to analyze the effects of HFEs to downstream resources will benefit from more accurate and precise measurements of the HFE release.

This project would install acoustic flow meters (AFMs) on each of the four bypass tubes to allow real time accurate measurement of the flow occurring through each bypass tube. The AFM instrumentation will also be installed on the outlet works in such a way as to be incorporated into the SCADA system like the AFMs already installed on each of the power penstocks.

To address safety concerns, during future HFEs, if AFMs have not been installed on the outlet works, the flow through each bypass tubes will be manually limited to no more than 3,750 cfs using a correction factor based on the current estimation of the error in the rating curves. The uncertainty of the error could result in releases from each bypass tube that is from about 0 to 500 cfs less than the safe capacity of 3,750 cfs. This potentially could reduce the peak release during HFEs by as much as 2,000 cfs from the intended peak.

Budget FY15 = $250,000 FY16 = $0 FY2017 = $0

Reclamation Project – Native Fish Conservation Contingency Fund—Funding History							
Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	$250,000	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	—	—	—	—	$250,000	—	—
DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	—	—	—	—	—	—	—
Total outsourced (%)	—	—	—	—	$250,000	—	—

C.6. Native Fish Conservation Contingency Fund

This budget item establishes a native fish conservation contingency fund. The goal of this budget item is to ensure that funds are available for nonnative fish control in the event this conservation action is needed for endangered humpback chub. This is a fund consisting of GCDAMP carryover funds from prior years and serves to ensure that funds are available for the control of nonnative fish should the need arise. This fund will implement nonnative fish control actions as defined in the 2007 and 2011 Opinions, and the NNFC EA and FONSI. Should excess funds become available beyond those needed for non-native fish control, these funds could be expended on other research, monitoring, and management actions that help conserve native fish. This fund will be incrementally increased with future carryover dollars when available.

In FY15 $364,052 will be used to fund several important fisheries research and monitoring projects that will benefit native fish species. Funding these projects will still allow for sufficient funds to conduct nonnative fish control should the need arise over the course of the FY15–17 period. These projects are identified and described in the GCMRC FY15–17 Budget and Work Plan, and include the following:

- 6.2 Aggregation recruitment $83,750
- 6.3 Monitoring mainstem aggregations with PIT tag antennas (pilot) $18,444
- 6.6 Direct mainstem augmentation of humpback chub $9,790
- 7.3 July Little Colorado River juvenile humpback chub marking to estimate production and outmigration $112,172
- 7.6 Potential for gravel substrate limitation for humpback chub reproduction in the LCR $11,600
- 7.7 Evaluate CO2 as a limiting factor early life history stages of humpback chub in the Little Colorado River $86,420
- 7.9 Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers $41,876

Budget FY15 = $824,079 FY16 = $1,110,894 FY2017 = $1,667,414

Reclamation Project – Native Fish Conservation Contingency Fund—Funding History							
Activity	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Outside Reclamation science/labor	—	—	—	—			
Logistics field support	—	—	—	—			
Project-related travel/training	—	—	—	—			
Operations/supplies	—	—	—	—			
Reclamation salaries	—	—	—	—			
Subtotal	49,049	50,521	782,660	667,947	824,079	1,110,894	1,667,414

DOI Overhead (35%)	—	—	—	—	—	—	—
Project total	49,049	50,521	782,660	667,947	824,079	1,110,894	1,667,414
Total outsourced (%)	—	—	—	—	—	—	—

D.1. Cultural Resources Program Administrative Costs

This budget funds the salary and travel expenses of BOR staff to administer the National Historic Preservation Act (NHPA) compliance for the GCDAMP. This includes the 1994 PA for Glen Canyon Dam Operations, the 2012 Memoranda of Agreement (MOA) documents for Non-native Fish Control and the HFE Protocol, and general needs of tribal consultation for the GCDAMP. This also includes BOR staff administration costs associated with maintaining the grants for tribal participation in the GCDAMP and tribal contracts to implement tribal monitoring protocols.

Project Goals and Objectives

- Management of five tribal grants from both appropriated funds for participation in the GCDAMP and power revenues to provide implementation of tribal monitoring protocols.
- Management of the monitoring and data recovery of at-risk historic properties and other related projects associated with implementation of NHPA compliance agreements for the operation of Glen Canyon Dam.
- Attending TWG and AMWG meetings, Cultural Ad Hoc Group meetings, and conducting meetings required by the 1994 PA and 2012 MOAs.

Compliance with the National Historic Preservation Act, Section 106 is the primary outcome of this project, which also ensures accountability for the tribal grants and contracts and appropriate use of both appropriated dollars and power revenues.

Budget FY15 = $135,249 FY16 = $139,307 FY17 = $143,486

Reclamation Project - Cultural Resources Program Administrative Costs—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	3,000	3,000	9,000	9,000	9,000	9,000	9,000
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	42,409	45,353	88,029	90,600	93,518	96,524	99,619
Subtotal	45,409	47,575	94,696	97,267	102,518	105,524	108,619
DOI Overhead (35%)	14,843	15,873	30,810	31,710	32,731	33,783	34,867
Project total	60,252	64,226	127,839	131,310	135,249	139,307	143,486
Total outsourced (%)	—	—	—	—	—	—	—

D.2. Cultural Resources Work Plan

1. Glen Canyon National Recreation Area Monitoring and Mitigation

In FY15, Glen Canyon NRA proposes to conduct data collection and monitoring of cultural resources at sites potentially affected by operations of the Glen Canyon Dam. Results from these efforts will inform the timing and scope of remedial action treatments proposed in out years for sites in Glen Canyon NRA. The FY15 scope of work includes two components: 1) implement the long-term monitoring program; and 2) conduct consultation with the five tribes to develop a plan of action to obtain tribal values. By so doing, Glen Canyon NRA gathers the data needed to assess effects on the sites, landscape and Traditional Cultural Property of Glen Canyon Reach. This work will help inform and be integrated into the long-term monitoring program proposed under Component 1 below.

<u>Component 1: Implement the Long-term Monitoring Program for Terrestrial and Submerged Cultural Resources</u>

Long-term monitoring of cultural resources in the Glen Canyon Reach is required under the Grand Canyon Protection Act. These activities were formally conducted annually from 1992 to 1998 and again in 2003. Stipulations in the MOA for the Glen Canyon Dam High Flow Experiment Protocol identify the need for monitoring programs to determine potential adverse effects to previously unidentified sites and to include assurances that programs efficiently and effectively gather the data needed to assess effects on locations of cultural and religious importance to Tribes. Glen Canyon NRA recognizes the limitations of its section 110 activities to fulfill the BOR's 106 obligations for the operations of Glen Canyon Dam. We therefore provide the following proposal for long-term monitoring activities to assist the BOR in meeting their compliance obligations.

Implementation of the proposed long-term monitoring program will be conducted by NPS through Glen Canyon NRA and coordinated with other NPS entities, the BOR, Grand Canyon Monitoring and Research Center (GCMRC), Tribes, and other stakeholders. Additional NPS entities involved will include Grand Canyon National Park, Submerged Resources Center (SRC), and Midwest Archeological Center. General monitoring methodologies will include periodic visual inspection, condition assessment, and evaluation via on-site monitoring and repeat photography. The format of monitoring data will be finalized following review and coordination with partners and stakeholders. Sites selected for monitoring will be chosen through a review of existing data on archeological sites that are potentially affected by Glen Canyon Dam operations and include a control group of sites for comparison. Timing for monitoring of all resources will coincide with a schedule appropriate for evaluating the potential effects of dam operations with an emphasis on effects resulting from the HFE Protocol. Summary reports will be completed and submitted annually.

In addition to terrestrial monitoring, the NPS SRC will continue monitor the submerged Spencer Steamboat (AZ: C: 02:011, Feature 12) for baseline data collection in April of 2014. Monitoring will continue if the report completed by NPS SRC recommends continued monitoring or mitigation.

In FY16 and FY17, Glen Canyon NRA proposes to continue data collection and monitoring of cultural resources at sites potentially affected by operations of the Glen Canyon Dam. Results from these efforts will inform the timing and scope of remedial action treatments proposed in out years for sites in Glen Canyon NRA.

Component 2: Address Tribal Values

Glen Canyon NRA will conduct consultation with the five tribes to determine the protocol by which tribal values will be gathered and used to inform monitoring and potentially mitigation of locations of cultural and religious importance. This information should contribute to long-term monitoring and/or mitigation through potential non-intrusive and/or intrusive excavation.

Budget FY15 = $61,000 FY16 = $145,000 FY17 = $104,000

2. Zuni Associative Values

When historic properties are valued for their association with important historical events and important people, mitigation may be accomplished by documenting those associations. This project mitigates for losses of these values through the production of a DVD. Zuni religious leaders will be interviewed and asked to express their views and feelings about the importance of Grand Canyon, the Colorado River, the Little Colorado River, Ribbon Falls, and Zuni ancestral archaeological sites in Zuni culture, heritage, and the continuing sense of Zuni community. The DVD will be recorded on location within the Grand Canyon. Zuni heritage themes discussed in the DVD will be the emergence, the creation of medicine bundles, the migrations, and the continuing relational spiritual connection between the Pueblo of Zuni and the Grand Canyon. The final DVD is intended for use in the Zuni school systems, available for the Zuni general public through the Zuni libraries, and for use in educating GCDAMP stakeholders about the Zuni relationship to Grand Canyon.

Budget FY15 = $100,000 FY16 = $30,000 FY17 = $0

3. Support for GCMRC's Project 4

This project will examine deposition of aeolian sand from HFE-created sand bars on historic properties within the area of potential effect of future dam operations. The primary objectives of element 4.2. are to 1) draft and 2) implement a monitoring plan that meets requirements for monitoring effects of dam operations to cultural resources relative to the National Historic Preservation Act and Grand Canyon Protection Act. The plan will be designed to identify whether, and how much, HFE sand is transported by wind to a representative sample of archaeological sites, and to measure the effect that wind transported sand has on site surface condition and site stability (i.e., the degree to which this mitigates effects from precipitation induced gully erosion and other surface impacts). Year 1 of the project will focus on drafting, reviewing, revising, and pursuing approval for the monitoring plan. Years 2 and 3 of the project will focus on implementing the monitoring plan. The draft plan will make a recommendation of the sample of archaeological sites that should be monitored, but stakeholders (presumably including the BOR, NPS, SHPO, ACHP and tribes) will need to work very closely with GCMRC in year 1 of the project to come to agreement on the monitoring protocol and set of sites that is ultimately monitored. The monitoring plan will be designed in the context of the archaeological site classification developed and applied in 2013 and 2014 which provides useful, site-specific expectations of landscape response to dam operations and controlled floods. While recent monitoring efforts have focused on the use of lidar to measure topographic changes, in drafting the monitoring plan, GCMRC will also consider the use of other monitoring methods and tools. Funding in FY 2015 also includes funding for tribal consultation and review of the monitoring plan.

Budget FY15 = $180,000 FY16 = $150,000 FY17 = $236,450

4. TEK Ecological Restoration Project

Based on the proposed completion of a Determination of Eligibility for Grand Canyon as a Hualapai TCP, this project will be a mitigation measure for vegetation that can be contributing elements to the TCP, such as the Gooddings Willow at Granite Park. The project will comprise planning (choosing collection areas and restoration sites), especially during the first year, site preparation (e.g., tamarisk removal if necessary), and some limited planting of certain species in select locations as pilot plots. Other aspects of the project are envisioned as longer term efforts, in particular propagating and nurturing Gooddings willow, cottonwood, and possibly other tree species, as well as research and monitoring for associated changes in ecological conditions.

Budget FY15 = $99,000 FY16 = $100,000 FY17 = $100,000

5. Tribal Synthesis

This project will increase the understanding of the Native American perspective within the GCDAMP by utilizing Traditional Ecological Knowledge (TEK). The project will evaluate the management of other river systems and the involvement of Native Americans, increase tribal participation in the GCDAMP planning and management process and integrate tribal perspectives into the AMP science program.

Budget FY15 = $0 FY16 = $50,000 FY17 = $70,000

6. Annual Integrated River Trip: An Exchange of Values and World-Views

The objective of this project is to provide an opportunity for tribal representatives and GCDAMP stakeholders to articulate their respective concerns and issues in a field situation. Each river trips will be agenda-driven and may also include restoration projects.

Budget FY15 = $30,000 FY16 = $30,000 FY17 = $30,000

7. Nonnative Fish Removal Consultation

This project provides funding to support ongoing tribal consultation-related expenses associated with implementation of the Nonnative Fish Control EA, FONSI, and NHPA MOA. Should mechanical removal of non-native fish be necessary, this funding would be used to support tribal consultation and tribal participation in nonnative fish control efforts.

Budget FY15 = $10,000 FY16 = $10,000 FY17 = $10,000

8. Tribal Preparation of Paperwork for DOE of Grand Canyon to National Register

This project provides funding to support and assist tribes to prepare the paperwork to prepare determinations of eligibility (DOE) of the Grand Canyon and contributing elements to the National Register of Historic Places as a Traditional Cultural Property. This would be done under criteria a and b.

Budget FY15 = $20,000 FY16 = $0 FY17 = $0

Summary budget table for cultural resources work plan.

FY	GLCA Treat/ Monitor	Zuni Assoc. Values	GCMRC Proj. 4	Tribal TEK Veg.	Tribal Synth.	Tribal River Trip	NN Removal Consult.	Tribal NRHP Nom.	Total
15	$61,000	$100,000	$180,000	$99,000	$0	$30,000	$10,000	$20,000	$500,000
16	$145,000	$30,000	$150,000	$100,000	$50,000	$30,000	$10,000	$0	$515,000
17	$104,000	$0	$236,450	$100,000	$50,000	$30,000	$10,000	$0	$530,450

D.3. Integrated Tribal Resources Monitoring

This budget item provides funds to identify traditional cultural properties (TCPs) and implement Native American monitoring protocols that were developed in FY 2007 and recommended by the TWG as part of efforts to develop a core-monitoring program.

In addition, the five GCDAMP Tribes (Hopi Tribe, Hualapai Tribe, Kaibab-Paiute Tribe, Pueblo of Zuni, and Navajo Nation) will work with BOR and the NPS to implement monitoring of historic properties in Glen and Grand Canyons. This will be accomplished by adding an additional 3 days to the annual GCDAMP monitoring trips.

The primary goal of this activity is to evaluate the effects of dam operations and other actions under the authority of the Secretary of the Interior on resources of value to Native American Tribes. A secondary goal is to conduct condition monitoring of historic properties to assist BOR in compliance with Section 106 of the National Historic Preservation Act.

Annual reports will be prepared detailing activities, findings, and monitoring data that result from implementing core-monitoring protocols for historic properties. Condition monitoring data will be provided to BOR to assist in prioritization of historic properties for treatment in subsequent years. In addition, monitoring data will be used to update NPS databases.

Budget FY15 = $162,227 FY16 = $167,094 FY17 = $172,107

Reclamation Project - Integrated Tribal Resources Monitoring—Funding History

Activity	2011	2012	2013	2014	2015	2016	2017
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal (power revenues)	144,553	148,889	157,160	161,875	162,227	167,094	172,107
DOI Overhead (35%)	—	—	—	—	—	—	—
Appropriated Funds	75,000	—	—	—	—	—	—
Project total	219,553	148,889	157,160	161,875	162,227	167,094	172,107
Total outsourced (%)	—	—	—	—	—	—	—

D.4. Tribal Participation in the GCDAMP

This budget item provides funding through agency appropriations (not power revenues) for the participation in GCDAMP meetings, resource monitoring, and government-to-government consultation of the five GCDAMP Tribes (Hopi Tribe, Hualapai Tribe, Kaibab Paiute Tribe, Pueblo of Zuni, Navajo Nation) and five DOI agencies (U.S. Geological Survey, National Park Service, BOR, U.S. Fish and Wildlife Service, and Bureau of Indian Affairs), with BOR serving as lead agency. The purpose of the funding is to ensure tribal viewpoints are integrated into continuing GCDAMP dialogs, votes, and in the final recommendations made to the Secretary of the Interior. The five DOI agencies provide appropriated funding to support this budget item.

Budget FY15 = $475,000 FY16 = $475,000 FY17 = $475,000

Reclamation Project E. Tribal Participation in the GCDAMP: Funding History							
Activity	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Outside Reclamation science/labor	—	—	—	—	—	—	—
Logistics field support	—	—	—	—	—	—	—
Project-related travel/training	—	—	—	—	—	—	—
Operations/supplies	—	—	—	—	—	—	—
Reclamation salaries	—	—	—	—	—	—	—
Subtotal	475,000	475,000	475,000	475,000	475,000	475,000	475,000
DOI Overhead (35%)							
Project total	475,000	475,000	475,000	475,000	475,000	475,000	475,000
Total outsourced (%)	100%	100%	100%	100%	100%	100%	100%

Glen Canyon Dam Adaptive Management Program

FY 2015-17 Preliminary Draft Budget for the Bureau of Reclamation

	Description				FY15 with 3.0% CPI	FY16 with 3.0% CPI	FY17 with 3.0% CPI
A. AMWG							
	Personnel Costs - Labor & Burden				196,530	202,425	208,498
	AMWG Member Travel Reimbursement				15,689	16,159	16,644
	AMWG Reclamation Travel Reimbursement				16,097	16,580	17,077
	Facilitation Contract				79,556	81,943	84,401
	POAHG Expenses - Labor, Burden, & Travel				63,054	64,945	66,893
	Other				9,047	9,318	9,598
	Subtotal				**379,972**	**391,371**	**403,112**
B. TWG							
	Personnel Costs - Labor				97,863	100,799	103,823
	TWG Member Travel Reimbursement				23,051	23,743	24,455
	Reclamation Travel				15,903	16,381	16,872
	TWG Chair / Facilitation				32,050	33,012	34,002
	Other				2,585	2,662	2,742
	Subtotal				**171,453**	**176,596**	**181,894**

C. OTHER							
	Admin Support NPS Permitting				137,319	140,046	144,166
	Contract Administration - Labor, Burden, Travel				45,362	46,723	48,124
	Science Advisor Contract				75,000	77,250	79,568
	Experimental Fund				286,815	552,920	569,507
	Installation of Acoustic Flow Meters in Glen Canyon Dam Jet Tubes				250,000	0	0
	Native Fish Conservation Contingency Fund				824.079	1,110,894	1,667,414
	Subtotal				**1,983,623**	**2,542,881**	**3,123,827**
D. CULTURAL PROGRAM							
	Reclamation Administration and Travel				135,249	139,307	143,486
	Cultural Resources Work Plan				500,000	515,000	530,450
	Integrated Tribal Resource Monitoring				162,227	167,094	172,107
	Subtotal				**797,476**	**821,401**	**846,043**
	Reclamation Power Revenue Costs Total				**3,017477**	**3,617,201**	**4,189,828**
	Reclamation Power Revenue Costs w/o Carryover				**2,143,398**	**2,206,307**	**2,272,414**

Glen Canyon Dam Adaptive Management Program

FY 2015-17 Preliminary Draft Budget for the Bureau of Reclamation

	Description				FY15	FY16	FY 17
OTHER APPROPRIATED FUNDS							
TRIBAL CONTRACTS (Appropriated Funds)							
	Hopi Tribe			95,000	95,000	95,000	95,000
	Hualapai Tribe			95,000	95,000	95,000	95,000
	Navajo Nation			95,000	95,000	95,000	95,000
	Pueblo of Zuni			95,000	95,000	95,000	95,000
	Kaibab Band of Paiute Indians			95,000	95,000	95,000	95,000
	DOI Agency Appropriated Funds Total			**$475,000**	**$475,000**	**$475,000**	**$475,000**
	Total			**$475,000**	**$3,492,477**	**4,092,201**	**$4,664,828**
	Total w/o Carryover				**$2,618,398**	**$2,681,307**	**$2,747,414**

Chapter 2. U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center Triennial Budget and Work Plan—Fiscal Years 2015–2017

Introduction

The Glen Canyon Dam Adaptive Management Program (GCDAMP) is an advisory process wherein protection and management of Colorado River resources downstream from Glen Canyon Dam are considered in planning dam operations. The Grand Canyon Protection Act of 1992 directs the Secretary of the Interior (the Secretary) to establish and implement long-term monitoring programs to ensure that Glen Canyon Dam is operated "… in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established…." The Final Environmental Impact Statement (EIS) for Operation of Glen Canyon Dam (U.S. Department of the Interior, 1995) recommended creation of a federal advisory committee to advise the Secretary on adaptive management of operations of the dam. The Record of Decision for the EIS that was signed in October 1996 created this federal advisory committee, and the charter of the Adaptive Management Work Group (AMWG) that implements the GCDAMP was signed in January 1997. Many stakeholders who are members of the AMWG also participate at a technical level in the Technical Work Group (TWG), and the TWG formulates recommendations about research and monitoring for consideration by the AMWG.

The USGS Grand Canyon Monitoring and Research Center (GCMRC) provides the primary science support for the GCDAMP, and this responsibility is described in numerous administrative documents. The 2002 Strategic Plan for the GCDAMP (Glen Canyon Dam Adaptive Management Work Group, 2002, p. 5) states that the GCMRC "serves as the science center for the Glen Canyon Dam Adaptive Management Program."

The GCDAMP budget is administered by the Bureau of Reclamation (Reclamation). One part of the GCDAMP budget supports Reclamation's administrative and staff travel costs, provides reimbursements to AMWG members and members of other GCDAMP committees and subcommittees, provides meeting facilitation and public outreach, and supports compliance activities. Reclamation funding, with equal support from four other agencies of the Department of the Interior, supports Native American tribal participation in many aspects of the program. These aspects of the program are described in Chapter 1.

Approximately 80 percent of the GCDAMP annual budget supports the monitoring and research work of the GCMRC. The GCMRC is formally organized as a research station within the USGS Southwest Biological Science Center. The GCMRC was originally organized as a small contracting office, and the majority of scientific work – field data collection and related analysis – was undertaken by contractors and collaborators, including universities, sister agencies, and private companies (Roles Ad Hoc Group of the Glen Canyon Dam Adaptive Management Work Group, 2008, p. 39-41.). With time, the proportion of monitoring and research work conducted by GCMRC staff has increased, and this trend of increasing science activity within GCMRC is also reflected in this work plan.

Purpose

In fiscal years 2015, 2016, and 2017 (FY15–17), the GCMRC and its cooperators will undertake monitoring and research activities about the status and trends of natural, cultural, and recreational resources of the Colorado River between Glen Canyon Dam and Lake Mead reservoir; this segment of the Colorado River is administratively termed the Colorado River ecosystem (CRe). The CRe is defined as "the Colorado River mainstem corridor and interacting resources in associated riparian and terrace zones, located primarily from the forebay of Glen Canyon Dam to the western boundary of Grand Canyon National Park." GCMRC will also continue to monitor the water quality of Lake Powell reservoir through a program that has been in place for approximately two decades. All activities to be conducted in the CRe are described in this Triennial Work Plan (TWP).

Administrative Guidance that Informs the FY15–17 Triennial Work Plan

Each project described in this TWP is organized around large monitoring and research themes. The monitoring and research themes identified in the FY15–17 TWP are those common to:

1. Assistant Secretary Castle's May 7, 2014, memo establishing the triennial budget process and clarifying priorities in GCMRC science planning;
2. the January 23, 2012, report of the Desired Future Conditions Ad Hoc Group of the AMWG that was adopted by AMWG in February 2012, discussed in Assistant Secretary Castle's February 29, 2012, memo to the AMWG, and accepted by Secretary Salazar in his April 30, 2012, memo;
3. the General Science Plan, Appendix B, Environmental Assessment: Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020 (Bureau of Reclamation, 2011a) (December 22, 2011);
4. the Research and Monitoring Plan, Appendix B, Environmental Assessment Non-Native Fish Control Downstream from Glen Canyon Dam (Bureau of Reclamation, 2011b) (December 22, 2011);
5. Assistant Secretary Castle's March 31, 2011, memo establishing priorities in GCMRC science planning;
6. the final draft Core Monitoring Plan (U. S. Geological Survey, 2011);
7. the strategic science plan prepared by GCMRC in March 2007 and amended in April 2009 (U. S. Geological Survey, 2007b);
8. the monitoring and research plan prepared by GCMRC, approved by AMWG in August 2007 and amended and approved in April 2009 (U.S. Geological Survey, 2007a); and,
9. 5 priority questions and the 12 program goals developed by the AMWG in 2004.

The monitoring and research themes described in the various GCDAMP documents and agreements written during the past decade concern (1) rehabilitation of the pre-dam physical template, especially regarding fine sediment; (2) maintenance of the food base on which the native fish community depends; (3) recovery of the endangered humpback chub (*Gila cypha*) and maintenance of populations of other native fish; (4) maintenance of the native riparian vegetation community; and, (5) maintenance of culturally important sites, including those that are of archaeological and historical significance. The various goals, questions, information needs, and desired future conditions developed by the various GCDAMP committees also recognize the importance of the nonnative rainbow trout (*Oncorhynchus mykiss*) fish population in Glen Canyon and the role played by nonnative riparian vegetation in providing habitat for some desired fauna. In addition to these resource considerations, delivery of water in accordance with the Law of the River and generation of renewable hydroelectricity are essential to the economic well-being of the Southwest. Thus, economic analysis of the various recommendations of the GCDAMP is another critical part of the GCDAMP.

Recent Guidance: Assistant Secretary Castle's May 7, 2014, Memo

The most recent guidance regarding Work Plan development was provided by Assistant Secretary Castle in May 2014. In that guidance, the Assistant Secretary reiterated guidance that she had provided in March 2011 that there are three science priorities: "science relevant to compliance with the Endangered Species Act, particularly relative to native fish and humpback chub; science informing our compliance with the Grand Canyon Protection Act, especially the sediment resource; and, science on non-native fish control and the recreational trout fishery … the need for this science continues." Additionally, the Assistant Secretary recognized that other priority issues included "understanding … how cultural and archaeological sites are linked to modern river processes and the role of Traditional Ecological Knowledge (TEK) in contributing to scientific understanding and river operations." Thus, the Assistant Secretary stated that, "I think these four issues (the three described in my 2011 memo and the evolving issue related to cultural/archaeological resources as linked to modern river processes) are the primary areas where GCMRC should concentrate its scientific resources."

The Assistant Secretary did not, however, preclude GCMRC from investigating other scientific topics in its monitoring and research work. She established, however, that such other investigations should focus on subjects and resources for which there is "widespread support and furthers the purposes of the Adaptive Management Program." The Assistant Secretary also directed GCMRC to continue "long-term monitoring of core ecosystem components." All activities must be conducted "within the relevant budget constraints."

Recent Guidance: Desired Future Conditions (January 2012 report; Adopted by AMWG February 2012; Reviewed and Accepted by the Secretary of the Interior April 30, 2012)

The Desired Future Conditions (DFCs) are statements of qualitative goals and objectives for the CRe and for operations of Glen Canyon Dam. These DFCs were developed by the Desired Future Conditions Ad Hoc Group (DFCAHG), adopted by the AMWG as a draft in August 2011, and revised, reconsidered, and adopted by the AMWG in February 2012. The DFCs are partly derived from 12 goals of the GCDAMP that had been developed in 2003, and the DFCs represent a clarification and refinement of these previously stated goals. In an August 19, 2011, memo to the AMWG commenting on the draft, Assistant Secretary Castle stated that, "The formulation of Desired Future Conditions is possibly the most important task the AMWG has undertaken in the last ten years," and the Assistant Secretary's February 29, 2012, memo to AMWG was no less enthusiastic. On April 30, 2012, Secretary of the Interior Salazar directed "the AMWG to utilize these DFCs to inform and guide the AMWG's future considerations, including advice and recommendations to me concerning the operations of Glen Canyon Dam and other related actions." In her April 26, 2012, memo to the Secretary, Assistant Secretary Castle described some of these related actions to include "future experimentation, research and monitoring, and the proactive development of future experimental plans." In response, GCMRC used these DFCs in the development of the FY15–17 Work Plan.

There are 9 DFCs that describe desired conditions in the CRe (Table 1). These DFCs “aim to maintain, enhance, and restore native species, natural habitats, and natural ecosystem processes” (Desired Future Conditions Ad Hoc Group, 2011). These DFCs concern the geophysical setting of the river, the quality of the Colorado River, the aquatic domain, and the riparian domain. One of the DFCs calls for re-establishment of “fishes extirpated from Grand Canyon.”

Table 1. Desired Future Conditions for the Colorado River ecosystem
Sediment-Related Resources
High elevation open riparian sediment deposits along the Colorado River in sufficient volume, area, and distribution so as to provide habitat to sustain native biota and desired ecosystem processes.
Water Quality
Water quality with regards to dissolved oxygen, nutrient concentrations and cycling, turbidity, temperature, etc., is sufficient to support natural ecosystem functions, visitor safety, and visitor experience to the extent feasible and consistent with the life history requirements of focal aquatic species.
Aquatic Domain
The aquatic food base will sustainably support viable populations of desired species at all trophic levels.
Assure that an adequate, diverse, productive aquatic foodbase exists for fish and other aquatic and terrestrial species that depend on those food resources.
Native fish species and their habitats … sustainably maintained throughout each species’ natural ranges in the CRe. (note: 6 supplementary criteria are articulated for humpback chub)
A high quality trout fishery in GCNRA … that does not adversely affect the native aquatic community in GCNP
Re-establish fishes extirpated from Grand Canyon, where feasible and consistent with recovery goals for humpback chub and the recovery goals of those extirpated fishes.
Native non-fish aquatic biota and their habitats are sustainably maintained with ecologically appropriate distributions.
Riparian Domain
Native riparian systems, in various stages of maturity, are diverse, healthy, productive, self-sustaining, and ecologically appropriate.

Additional information in the form of metrics that might inform the GCDAMP regarding progress towards achieving these DFCs was also described by the DFCAHG. Four metrics related to the CRe were proposed: critical habitat, species condition, carrying capacity thresholds, and populations. The population of key fish species (TWP Projects 6, 7, 9) and abundance and distribution of invertebrates at different life stages (TWP Project 5) are measured or estimated in this TWP. New work is proposed to investigate characteristics of the terrestrial fauna (TWP Project 11.4); on-going work describes characteristics of the riparian vegetation communities (TWP Project 11).

The FY15–17 TWP is responsive to most, but not all, of these DFCs. No studies are proposed related to introduction of extirpated species. Guidance to GCMRC from the AMWG, TWG, and sister agencies has not been sufficiently clear to allow GCMRC to confidently develop a research program that would inform introductions of extirpated species into the CRe. There is not yet consensus among stakeholders or agencies as to the species that might be reintroduced, the magnitude of the effort that might support introduction, or the spatial scope of such introduction. Until such time as reintroduction plans are described in administrative guidance, GCMRC is not in a position to make decisions about budget allocations on this topic. Another category of DFCs concerns hydropower. The DFCs state that, "Glen Canyon Dam capacity and energy is maintained and increased, so as to produce the greatest practicable amount of power and energy … Ensure continued delivery of … hydropower to the existing customers … [and] Maintain … operational flexibility." Other DFCs concern maximizing the "environmental benefits of hydropower generation" and minimizing "carbon emissions through hydropower generation." Seven metrics were proposed by the DFCAHG that describe aspects of these DFCs. These DFCs and metrics are not explicitly addressed in this Work Plan. Many of these metrics are reported by the Western Area Power Administration, and the Long-Term Experiment and Management Plan (LTEMP) EIS program is calculating several of the metrics in evaluating the performance of various EIS alternatives.

Two categories of DFCs related to cultural resources were defined by the DFCAHG. As concerns prehistoric archaeological and historic sites, the DFCAHG report stated that, "To the extent feasible, maintain significance and integrity [of these sites] through preservation in place." The DFCAHG report established that the attributes of Traditional Cultural Properties (TCPs) should be "maintained such that National Register eligibility is not compromised." Additionally, "Culturally appropriate conditions of resources are maintained based on traditional ecological knowledge." The role of traditional ecological knowledge was also emphasized in regards to resources of traditional cultural significance that are not NRHP [i.e., National Register of Historic Places] eligible – "Maintain culturally appropriate resource conditions based on traditional ecological knowledge, and integrate this desired condition into monitoring and management programs." Field data and metrics regarding cultural resources were proposed, and these measurements are included as part of TWP Project 4. As regards TCPs, the DFCAHG stated that, "Because culture defines the roles that resources play in that culture, only members of that culture can assess the status or health of the resources." In the course of developing draft proposals for the work described in this TWP, the GCMRC made several changes to specifically include workshops and tribal participation, especially for TWP Projects 4 and 12.

Recreation DFCs "describe goals and objectives for human use" of the CRe; these DFCs were divided into 4 categories: river recreation in Grand Canyon National Park (GCNP), river recreation in Glen Canyon National Recreation Area (GCNRA), the blue ribbon trout fishery in GCNRA, and river corridor stewardship. Of note are DFCs specific to GCNP that state that "maximum opportunity to experience the wilderness character of the canyon [be provided] … [the] river corridor landscape .. matches natural conditions as closely as possible, including extensive beaches and abundant driftwood … including a biotic community dominated in most instances by native species … a dynamic river ecosystem characterized by ecological patterns and processes within their range of natural variability … numerous campable sand bars distributed throughout the canyon." In the Glen Canyon segment of the CRe, the DFCs call for "camping beaches suitable for recreational use [and] a setting and ecosystem that is as close to natural conditions as possible." The recreation DFCs also call for "a high-quality sustainable recreational trout fishery" in GCNRA and that Glen Canyon Dam should be operated "to achieve the greatest benefit to the trout fishery … without causing excessive detriment to other resources."

Thirteen metrics were identified that are useful in measuring the performance of the GCDAMP as regards desired recreation experiences in the CRe. Some of these metrics are measured in TWP Project 13.1, and other metrics are being investigated by the National Park Service as part of the LTEMP EIS process. However, no studies are proposed in this TWP concerning: (1) “socio-economic value of … the Grand Canyon itself, as a whole,” and (2) “factors that make up the ‘wilderness character’ of the river corridor.” Two metrics identified by the Ad Hoc Group that concern fish – the effect of trout on the ecosystem and the characteristics most valued for the trout fishery – are the foci of TWP Projects 9 and 13.1. “Water quality variables that influence river recreation” are measured in TWP Projects 1 and 2.

It is notable that one of the recreation DFCs states that “Recreational and wilderness experiences [are] minimally affected by research and management activities.” It is unavoidable that scientific activities have the potential to affect wilderness experiences, such as when motors are used during the non-motor boating season in GCNP and where cableways remain in place to facilitate stream-flow gaging. Recreational experiences are potentially affected by motor use, especially when research boats travel upstream or at night, or large, semi-permanent camps are established. All research activities in GCNRA and GCNP occur after review and issuing of permits by the National Park Service. GCMRC and its cooperators/collaborators work with the National Park Service to ensure that adverse impacts of its scientific activities are minimized.
In its January 2012 report, the DFCAHG stated that the DFCs “are intended to be … realistic and achievable through the operation of Glen Canyon Dam and related activities, subject to the Law of the River and other laws and authorities and consistent with the Grand Canyon Protection Act. These DFCs may not be entirely or collectively achievable – there will be tradeoffs and inherent limitations. This fact does not diminish their value.” Thus, the DFCs played a critical role in helping GCMRC focus its scientific attention.

In many cases, the DFCs reflect contrasting visions of the CRe. It is not obvious how the river corridor can “match natural conditions … including extensive beaches” when more than 95% of the pre-dam fine sediment once supplied to the CRe is now deposited in Lake Powell. In other cases, DFCs are mutually complementary, such as achieving “river flows that continue to be within a range that is reasonably safe” by flood control and hydropower production at Glen Canyon Dam. The challenge of maintaining “a high-quality sustainable recreational trout fishery” in Glen Canyon “that does not adversely affect the native aquatic community” in Marble and Grand Canyons remains a fundamental fish management challenge, and fish management policy is grounded on the substantial monitoring and research program described in TWP Projects 5, 6, 7, 8, 9, and 10. Schmidt and others (1998) characterized a similar range of goals that were articulated by stakeholders in the 1990s as the incompatible challenge of maximizing resources that are relicts of the pre-dam river and those that are artifacts of a dam-regulated river. The challenge of managing the river corridor for such a wide range of resource values is one reason for the complexity of the monitoring and research proposed in FY15–17. The scientific activities that will be undertaken in FY15–17 seek to describe and quantify the complex interactions among pre-dam relict and post-dam artifact resources that are affected by different reservoir release regimes; to distinguish between short term fluctuations and long-term trends, and to identify critical thresholds that may cause essential ecosystem changes to become progressive, rather than self-regulating. Despite these challenges, the DFCs provide a clear range of resources that defined the scope of GCMRC’s proposed activities.

<u>Recent Guidance: General Science Plan for Monitoring and Research of a High-Flow Experiment (HFE) Protocol at Glen Canyon Dam (December 2011)</u>

This general science plan describes activities that "will initially evaluate the effectiveness of high-flow releases under the HFE Protocol." Wright and Kennedy (2011) provided scientific direction relevant to the primary focus of HFE Protocol science activities, that concern the long-term behavior of sand bars and changes in the populations and distribution of rainbow trout and of humpback chub:

A logical next step in the adaptive-management process of the GCDAMP is to evaluate the cumulative effects of multiple HFEs over longer periods of time. This would be helpful because it is still uncertain whether sandbar building during HFEs can offset or exceed the sandbar erosion that occurs during periods of typical dam operations between HFEs. Thus, it is important to consider the frequency of HFEs and the erosion of sandbars between HFEs for future HFE planning. The fundamental sandbar-related science question therefore is:

- *Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?*

Based on studies that have been conducted to date, HFEs do not appear to be a tool that can be used to benefit humpback chub. Rainbow trout pose a threat to juvenile humpback chub rearing in the mainstem near the confluence with the Little Colorado River due to increased competition and predation. … natural-resource managers might consider proceeding with caution when implementing any HFE strategies, particularly those involving frequent spring-time events, because currently (2010) the biological response to HFEs appears to be inconsistent with management goals for humpback chub. A logical next step in the HFE process is evaluating whether the seasonal timing of HFEs affects the rainbow trout recruitment response. If fall-timed HFEs do not lead to increases in rainbow trout populations near the confluence with the Little Colorado River (or it is later demonstrated that rainbow trout do not exert strong influence on humpback chub rearing), then managers might be able to balance goals for sandbars and native fish without the need for substantial rainbow trout mitigation or removal. The fundamental fish-related science question therefore is:

- *Does the seasonal timing of HFEs influence the rainbow trout response?*

An adaptive-management process for HFE decision-making would be flexible and incorporate relevant scientific information, such as near real-time information about sediment conditions downstream from the dam and information on adult population trends for rainbow trout and humpback chub, as well as other resources. Indeed, as more HFEs are conducted, strong links connecting other resources to dam operations may be identified and incorporated into subsequent HFE strategies. An integrated science-based strategy would allow for effective management of the available post-dam sand supply while considering the impacts of the strategy on other resources within an adaptive-management framework.

In addition to these science questions related to sediment resources and fish, other science monitoring work focuses on assessing the effects of HFEs on the aquatic food base, riparian vegetation and springs habitat, recreational camping beaches, and archaeological sites. Specific components of the general science plan that are fulfilled by the FY15–17 TWP include Lake Powell and Colorado River water quality monitoring (Project 1), monitoring suspended sediment flux (TWP Project 2), monitoring within-channel and high-elevation sediment storage (TWP Project 3), monitoring archaeological site condition and stability (TWP Project 4), monitoring the aquatic food base (TWP Project 5), and riparian vegetation monitoring (TWP Project 11). The general science plan describes monitoring of changes in Kanab ambersnail

(*Oxyloma haydeni kanabense*) habitat at Vaseys Paradise. This monitoring work is not proposed in FY15—17, because the US Fish and Wildlife Service noted in its 2011 Biological Opinion for the HFE Protocol EA that HFEs will not adversely affect Kanab ambersnail habitat. Thus, only periodic monitoring of the snail population is required, especially in light of the findings of Culver and others (2013) who concluded that Kanab ambersnail are not a unique species. If this finding is confirmed, downlisting or delisting of this snail population might result. The general science plan also describes evaluations of the effects to hydropower generation of HFEs; these data are developed by the Western Area Power Administration.

Recent Guidance: Research and Monitoring Plan in Support of the Environmental Assessment Non-Native Fish Control Downstream from Glen Canyon Dam (December 2011)

The proposed action described in the Non-Native Fish Control (NNFC) EA is to control nonnative fish as a means of conserving the humpback chub and other native fishes. This action is predicated on fundamental observations concerning the nature of interactions between humpback chub and trout. Several aspects of these interactions have large scientific uncertainty. Consequently, the proposed action of the NNFC EA will be pursued in an adaptive management framework such that management actions undertaken in later years will be informed by monitoring and research conducted during the first years of implementation. Thus, the context of the research and monitoring plan is the effort to reduce uncertainty of management actions and to revise these actions as knowledge is gained throughout the 10-year duration of the EA. The GCMRC and its science cooperators identified 5 objectives to be addressed by their science activities associated with this EA:

Understand the relative roles of the LCR and the mainstem Colorado River in juvenile humpback chub survival rates and recruitment into the adult humpback chub population;
Determine the linkage between nonnative fish abundance and juvenile humpback chub abundance and survival rates in the LCR reach and elsewhere in Grand Canyon;
Determine the natal origins of rainbow trout found in Marble Canyon (river miles 8 to 56) and the LCR reach;
Assess the efficacy of nonnative fish removal in the PBR reach for rainbow trout and Upper Granite Gorge for brown trout; and
Assess the efficacy of flow manipulations to manage trout populations in the mainstem Colorado River from Lees Ferry to the LCR reach.

Since adoption of the Record of Decision that followed this EA, there has been no trout removal near the Little Colorado River confluence or between Lees Ferry and Badger Creek Rapids. Brown trout (*Salmo trutta*) and rainbow trout removal in and near Bright Angel Creek by Grand Canyon National Park staff with assistance from GCMRC, however, has occurred following adoption of Grand Canyon National Park's Comprehensive Fisheries Management Plan (National Park Service 2013). Thus, the research and monitoring plan described in this EA has not been specifically implemented, but monitoring and research activities undertaken in FY13–14 and planned for FY15–17 in this TWP specifically address each of the 5 objectives of the NNFC EA.

Recent Guidance: Assistant Secretary Castle’s March 31, 2011, memo to U.S. Geological Survey

Assistant Secretary Castle provided guidance to GCMRC in a March 2011 memo addressed to USGS Southwest Biological Science Center Director Kitchell and others. The Assistant

Secretary recognized that "very limited budgets" necessitated that "we need to focus on priorities." The DFCs, that were still being debated at the time of this memo, were "very comprehensive;" thus, the Assistant Secretary stated that "we also have to narrow the field." The priorities that were articulated were (1) "compliance with the Endangered Species Act, which means focus on the native fish and particularly the humpback chub," (2) "focus on sediment, which was an instigating factor for the Grand Canyon Protection Act and continues to be an issue with resources downstream of the dam,' and (3) "science on both non-native fish control and the recreational trout fishery." The Assistant Secretary argued that these priorities were very similar to those adopted by the AMWG in August 2004, and thus there was continuity in her recommendations to decisions by the AMWG in the past. As described above, the Assistant Secretary's 2014 memo reiterated these priorities, but added a priority related to the science that is related to cultural resource management. In addition, the Assistant Secretary reaffirmed her commitment that core monitoring activities must be continued while research focused on the priority research questions is pursued.

Recent Guidance: final draft General Core Monitoring Plan, February 18, 2011

A final draft General Core Monitoring Plan was developed by GCMRC for TWG review in February 2011. Although only the first step of an anticipated 4-step process, the general Core Monitoring Plan (CMP) culminated a decade of science planning activities undertaken by the AMWG, TWG, and GCMRC and continues to play a significant role in monitoring and research planning. Subsequent prioritization of management and research questions by the Department of the Interior, development of the DFCs, department-level policy actions such as the HFE Protocol, and new policy initiatives such as the LTEMP EIS have necessitated modification of the CMP implementation plan described in February 2011. Nevertheless, this final draft CMP represented a significant achievement in establishing a framework for evaluating potential scientific activities required to support the work of the AMWG, and no subsequent guidance or action by the Department of the Interior, its agencies, or the AMWG has substantially invalidated the monitoring framework described in this plan.

The concept of core monitoring and efforts to develop a core monitoring plan

Core monitoring is "consistent, long-term, repeated measurements using scientifically accepted protocols to measure status and trends of key resources … potentially affected by GCD operations." Additionally, "monitoring is also necessary to ensure compliance with other environmental statutes, including the Endangered Species Act and the National Historic Preservation Act." The scope of the CMP was based on Core Monitoring Information Needs (CMINs) defined by the AMWG in its 2003 Strategic Plan that were subsequently modified and prioritized by a 2005 Science Planning Group. The final draft CMP was responsive to most, but not all, of the higher priority CMINs; as such, the need for prioritization of information needs anticipated subsequent guidance memos provided by the Assistant Secretary in 2011 and 2014, as described above. At the time of publication of the CMP, TWG requested GCMRC to develop individual draft core monitoring plans responsive to each of the 12 Adaptive Management Program goals (GCDAMP, 2003), and each individual plan would include three monitoring options responsive to "high," "medium," and "low" funding availability. Such a tiered suite of options has not been developed for most resources, and the monitoring activities proposed in the FY15–17 TWP represent GCMRC's best professional judgment concerning how to collect critical data about resource condition and ecosystem processes for those resources that have been identified as of highest priority in the policy guidance documents described above.

The earliest monitoring in the CRe was the measurement of stream flow at Lees Ferry that began in 1921 (Topping and others, 2003). Ecological inventories were initiated by the National Park Service in the early 1970s, and Reclamation's Glen Canyon Environmental Studies (GCES) program began in 1983. The CMP provides an in-depth administrative history of monitoring programs since the inception of GCES and provides observations as to why development of a core monitoring program has been slow despite the universal recognition of the importance of such an effort. The factors slowing the development of a core monitoring program include disagreement about which resources ought to be monitored, disagreement about the acceptable levels of accuracy and precision of resource data needed to guide management, the absence of an ecosystem perspective in monitoring, and the absence of reliable predictive models to guide budget allocations for monitoring. The effort that culminated with the final draft CMP in 2011 was initiated early in 2006 when GCMRC Chief Hamill initiated development of a series of science planning documents, the last of which was the CMP.

Assessing GCDAMP monitoring needs

Monitoring should be pursued within an ecosystem context. In that context, the CMP set the direction for subsequent development of DFCs and the present organization of the TWP. The CMP was organized around the 12 GCDAMP goals and distinguished between ecosystem resources and ecosystem drivers. Ecosystem resources were native fish, extirpated species, Kanab ambersnail, spring and riparian habitats, recreational resources, cultural resources, and hydropower. Ecosystem drivers were the aquatic and terrestrial food web, stream flow, water quality, sediment transport, and sediment supply. As discussed below, the FY 15–17 TWP builds on this organizing framework, because the DFCs that guide the TWP are modeled on the original 12 GCDAMP goals.

The CMP stated that, "The core monitoring program … is intended to inform managers and stakeholders as to whether AMP goals and objectives ... are being met." The CMP focused on the 12 GCDAMP goals but anticipated that this organizational framework would be revised and potentially reorganized once DFCs were established. The CMP recognized that core monitoring is not only linked with management goals, but is also linked with research activities and the development of modeling tools. The CMP recognized that core monitoring should be linked with monitoring efforts elsewhere in the Colorado River watershed and other U.S. southwest rivers, and with the management objectives of sister federal agencies.

Previous BWP documents of the GCMRC were also organized around the GCDAMP Program Goals. However, in the reorganization of the Work Plan represented in the FY13–14 document and carried forward in the FY15–17 TWP, the various goals associated with the aquatic domain (Goals 1, 2, 3, and 4) were reorganized into TWP Projects 5, 6, 7, 8, 9. Program Goal 5 concerns the Kanab ambersnail, and there are no activities proposed in FY15–17 on this topic. Program Goal 6 is the focus of TWP Project 11 in the FY15–17 TWP. Goal 7 is the focus of TWP Projects 1 and 2, and Goal 8 is the focus of TWP Project 3. Goal 9 is, at least in part, the focus of TWP Projects 3 (camping beaches), 6 (creel surveys), and 13 (economic values of recreational resources). Goal 10 is not explicitly evaluated in the TWP. TWP Project 4 and 12 represent an expanded focus on Goal 11.

The monitoring methods described in the FY15–17 TWP represent a substantial scientific advancement in developing formalized protocols for regular measurement of key river resources.

In the case of protocols for measuring sand bars (TWP Project 3), sediment transport and water quality (TWP Project 2), humpback chub and rainbow trout populations and status and trends of other fish species (TWP Projects 6, 7, 8, 9), and monitoring vegetation communities (TWP Project 11), GCMRC has worked with sister agencies and collaborators to develop efficient protocols that take advantage of large bodies of historical data, address issues of how to extrapolate site scale measurements to the entire CRe, and how to estimate temporal trends in key resources. The next step in the formalization of monitoring protocols will be to take the advancements described in the TWP and incorporate these into a revised General Core Monitoring Plan.

Overview of the FY 15–17 Triennial Work Plan

The FY15–17 Triennial Work Plan follows the structure of the FY13–14 BWP which simplified and consolidated GCMRC's research and monitoring activities into larger projects focused on significant natural and socioeconomic resource questions and resource conditions. There are twelve projects (TWP Project 1 – TWP Project 12) in the fields of physical, biological, and cultural resource sciences. TWP Project 13 focuses on socioeconomic monitoring and research. Other funds support independent reviews, GIS services and support, and administration of the GCMRC.

The FY15–17 TWP undertakes monitoring *and* research. Two types of monitoring activities are undertaken: (1) monitoring of ecosystem resources and processes by which the GCDAMP can evaluate progress towards achieving the DFCs, and (2) monitoring that is essential for implementing the HFE Protocol or evaluating its success and monitoring the triggering criteria toed to the NNFC EA. There are three major categories of research activities: (1) research concerning technical and analytical innovation in monitoring, (2) research that will lead to improved predictive modeling capacity, and (3) research to resolve key scientific uncertainties. In some cases, research will address key uncertainties identified in the HFE Protocol and NNFC EAs. In some cases, research activities seek to resolve key uncertainties that have emerged in the past two years during preparation of the LTEMP EIS, especially in the development of better modeling tools with which to make predictions about resource response under different prevailing climate and reservoir release regimes. Three project elements support independent science oversight and review. Project 12 seeks to further integrate tribes into monitoring and research by specifically focusing on terrestrial resources upslope from the active channel.

Because the DFCs are comprehensive and implementation of a monitoring and research plan to fully address every DFC with high accuracy, high precision, and low uncertainty is beyond the budget limits of the GCDAMP, GCMRC focused its attention on those DFCs that are related to the monitoring and research priorities identified by Assistant Secretary Castle in her 2014 memo. Additionally, because the HFE Protocol and NNFC are administrative policy actions that are presently in place and because GCMRC monitoring activities are essential for implementation of this policy, related science activities were considered of high priority. GCMRC also recognized that TWP Project 2 follows the Goal 7 Core Monitoring Program that was extensively discussed in 2007 and 2008 and has not been substantially changed since that time.

Projects that specifically support implementation of monitoring, either as core activities, or in support of the HFE Protocol or NNFC, total approximately $4.2 million in FY15. Most of these projects continue in FY16 and FY17 (Table 2). Research projects, totaling approximately $3.3 million in FY15 and are distinguished by purpose (See Appendix 2-A). Many research projects are identified as 2-year projects, but would continue for 3 years if additional funding becomes available.

Table 2. Monitoring activities to be conducted in Triennial Work Plan			
Project Identifier	Project Element	Funding[1]	Desired future condition or policy implementation
Monitoring protocols well established with peer-reviewed, scientifically accepted methods			
2	**Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem**	**$1,343,000 (FY15) $1,457,000 (FY16) $1,540,000 (FY17)**	**Water quality element of CRe DFC; HFE Protocol implementation**
Critical resource, monitoring protocol being developed			
Project Identifier	Project Element		**Desired future condition or policy implementation** -or- *Funding*[1]
3	**Sandbars and Sediment Storage Dynamics**		**Sediment element of CRe DFC; HFE Protocol evaluation**
3.1.1	*Monitoring sandbars using topographic surveys and remote cameras*		*$370,000 (FY15) $355,000 (FY16) $372,000 (FY17)*
3.1.2	*Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing*		*$120,000 (FY15) $131,000 (FY16) $141,000 (FY17)*
3.2	*Sediment storage monitoring*		*$460,000 (FY15) $520,000 (FY16)*
3.5	*Control network and survey support*		*$109,000 (FY15) $147,000 (FY16) $156,000 (FY17)*
Project Identifier	Project Element		**Desired future condition or policy implementation** -or- *Funding*[1]
4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**Cultural resources DFC; HFE Protocol evaluation**
4.2	*Monitoring of cultural sites in Grand and Glen Canyons*		*$124,000 (FY15) $349,000 (FY16) $340,000 (FY17)*
Project Identifier	Project Element		**Desired future condition or policy implementation** -or- *Funding*[1]
5	**Food Base Monitoring and Research**		**Aquatic domain element of CRe DFC**
5.1.1	*Insect emergence in Grand Canyon via citizen science*		*$117,600 (FY15) $119,500 (FY16)*

		$138,200 (FY17)
5.2.1	*Continue characterizing and monitoring drift and insect emergence in Glen Canyon*	*$51,900 (FY15)* *$66,900 (FY16)* *$88,40 (FY17)*
5.2.2	*Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons*	*$87,100 (FY15)* *$115,600 (FY16)* *$157,30 (FY17)*
5.3.2	*Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon*	*$15,300 (FY15)* *$16,700 (FY16)* *$18,300 (FY17)*
Project Identifier	Project Element	**Desired future condition or policy implementation** -or- *Funding*[1]
6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Community Dynamics**	**Native species component of aquatic domain element of CRe DFC; HFE Protocol and NNFC evaluation**
6.1	*Mainstem Colorado River Humpback Chub aggregation monitoring*	*$217,700 (FY15)* *$241,600 (FY16)* *$249,40 (FY17)*
6.4	*System Wide Electrofishing*	*$273,100 (FY15)* *$279,700 (FY16)* *$316,400 (FY17)*
6.7	*Rainbow Trout Early Life Stage Survey*	*$76,800 (FY15)* *$79,100 (FY16)* *$90,100 (FY17)*
6.8	*Lees Ferry Creel Survey*	
Project Identifier	Project Element	**Desired future condition or policy implementation** -or- *Funding*[1]
7	**Population Ecology of Humpback Chub in and around the Little Colorado River**	**Native species component of aquatic domain element of CRe DFC; HFE Protocol and NNFC evaluation**
7.1	*Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River*	*$530,800 (FY15)* *$542,800 (FY16)* *$554,50 (FY17)*
7.2	*Juvenile chub monitoring in the mainstem near the Little Colorado River confluence*	*$450,700 (FY15)* *$468,100 (FY16)* *$181,900 (FY17)*
7.4	*Remote PIT tag array monitoring in the LCR*	*$53,500 (FY15)* *$111,100 (FY16)* *$152,500 (FY17)*
7.8	*Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub*	*$16,800 (FY15)* *$16,700 (FY16)* *$18,30 (FY17)*
7.10	*Humpback chub population modelling*	*$97,200 (FY15)* *$149,400 (FY16)*

		$209,400 (FY17)
Project Identifier	Project Element	**Desired future condition or policy implementation** -or- *Funding*[1]
8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**	**Native species component of aquatic domain element of CRe DFC**
8.2	*Translocation and monitoring above Chute Falls*	*$88,600 (FY15)* *$87,500 (FY16)* *$88,000 (FY17)*
8.4	*Invasive Species Surveillance and Response*	*$52,000 (FY17)*
Project Identifier	Project Element	**Desired future condition or policy implementation** -or- *Funding*[1]
9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**	**Rainbow trout component of aquatic domain element of CRe DFC; Blue ribbon trout fishery component of recreation element of DFC**
9.1	*Lees Ferry RBT; monitoring, analysis, and study design*	*$180,900 (FY15)* *$212,700 (FY16)* *$76,900 (FY17)*
9.2	*Detection of RBT movement from upper Colorado River below GCD (NO)*	*$352,500 (FY15)* *$436,500 (FY16)* *$370,300 (FY17)*
9.9	*Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management*	*$72,400 (FY15)* *$61,800 (FY16)* *$98,500 (FY17)*
Project Identifier	Project Element	**Desired future condition or policy implementation** -or- *Funding*[1]
11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**	**Riparian domain element of CRe DFC**
11.1	*Ground-based vegetation monitoring*	*$176,000 (FY15)* *$190,900 (FY16)* *$211,900 (FY17)*
11.2	*Periodic landscape scale vegetation mapping and analysis using remotely sensed data*	*$154,700 (FY15)* *$127,200 (FY16)* *$133,100 (FY17)*

[1]Actual funding levels for all FY16 and FY17 projects will be reduced by 7% and 5%, respectively. Project element total costs listed in this table reflect estimated costs before these reductions.

How the Work Plan Was Developed

Development of this TWP began in earnest in late January when the GCMRC convened a knowledge assessment and annual reporting meeting. This meeting was immediately followed by a TWG meeting during which the needs of stakeholders were assessed. The annual reporting meeting focused on topics that were identified jointly by GCMRC and its cooperators, TWG members, and sister agencies. In December 2013 and January 2014, ad hoc groups of the TWG and interagency/cooperator researcher meetings were held to solicit monitoring and research recommendations from stakeholders. For example, the Socio-Economic Ad Hoc Group (SEAHG) met in January 2014 and made recommendations for projects to be conducted in FY15–17; TWP Project 13 is responsive to those recommendations.

Thereafter, the GCMRC received direct input from numerous stakeholders and met with the Budget Ad Hoc Group (BAHG) in mid-February. BAHG members provided direction and suggestions on 47 topics that concern nearly every project in the TWP. In some cases, suggestions were expansive and concerned the geographic scope of GCMRC's investigations or the need to expand experimental work and develop an experimental facility near the Colorado River. Other suggestions were of small scale and of a detailed nature. In other cases, BAHG suggestions were directed at Reclamation's part of the budget that is described in Chapter 1 of this TWP. It was not possible to directly address every suggestion made by the BAHG due to budget limitations, policy direction, or conflicting management objectives. Nevertheless, GCMRC considered all BAHG comments and suggestions and engaged in an open and transparent discussion with stakeholders in the course of developing the projects described here. The timely nature of the BAHG suggestions – prior to development of the first draft of the projects included in this TWP – ensured that the many BAHG suggestions were incorporated to the degree possible.

Discussions among the GCMRC staff, stakeholders, agency staff, and cooperators continued in March and the TWG met in early April to formally make recommendations on how the TWP should be developed. Nine major topic areas were identified; in some cases, 2 suggestions were provided in a topic area and in other cases, 7-9 suggestions were made (Appendix 4). A high proportion of suggestions concerned fish monitoring and research. In most cases, the TWG supported the project ideas that were developed by the GCMRC staff and cooperators and asked for more detail in a variety of areas including proposed methods, sampling design, and study objectives. The GCMRC has been responsive to these requests by providing in this TWP thorough scientific backgrounds and justifications, hypotheses to be tested, and descriptions of each proposed study. The only explicit recommendation to decrease monitoring concerned potentially redundant sampling in the most downstream part of the Little Colorado River, and the sampling program proposed in this TWP reflects that suggestion.

The GCMRC provided the TWG and Science Advisors a prospectus of the TWP in mid-May that included a webinar and a draft document that included the project summaries and preliminary budget allocation. On June 6, the GCMRC published the draft TWP, and Reclamation posted this document on their GCDAMP website. This draft was reviewed by the Science Advisors, who provided their review to the TWG at its June 24 meeting. The GCMRC staff revised the TWP in response to input from the TWG and Science Advisors received in late June; staff also developed a formal Response to Reviewer Comments that is a companion document to this TWP.

Budget allocations

In most cases, GCMRC staff had lead responsibility to develop each project, and each lead investigator collaborated with staff of sister agencies, long-time university and private sector cooperators, and others to review the state of knowledge regarding monitoring protocols and to identify critical scientific uncertainties. Projects were organized around central themes that primarily followed the organization of the FY13–14 Work Plan. New projects were added in food base (TWP Project 5), habitat considerations in the Glen Canyon Dam tailwater (TWP Project 10), assessing cultural values in the terrestrial ecosystem (TWP Project 12), and socioeconomics (TWP Project 13). The fish ecology projects were reorganized from five to four projects.

As the draft TWP emerged as a comprehensive document, it was clear that more potential monitoring and research projects were proposed than available funds could support. The full suite of projects that were proposed by GCMRC staff and collaborators were discussed with the TWG so that stakeholder and agency support and interest – or lack of support and interest – could be elicited.

In the June 6 draft, the GCMRC presented a work plan that described activities that is generally consistent with anticipated funding availability, but a small proportion of unfunded projects had strong stakeholder support. In response, the GCMRC re-evaluated its proposed allocation of budget resources, and the description of projects and budget support is responsive to the TWG input received in June and in a July webinar. Final prioritization of project was based on the following criteria, beginning with the most important projects:

1. Monitoring projects that implement the HFE Protocol and NNFC EAs;
2. Monitoring projects that evaluate the effectiveness of the HFE Protocol and NNFC EAs;
3. Other core monitoring activities;
4. Creating independent science review panels on critical issues;
5. Advancing the integration of tribal concerns into monitoring and research;
6. Research that advances monitoring techniques and analytical methods;
7. Research that advances predictive modeling capabilities; and,
8. Research to resolve critical scientific uncertainties.

Six projects related to native fish research will be funded in FY15 by reallocation of funds from Reclamation's Native Fish Conservation Contingency Fund, as described in Chapter 1. Reclamation also allocated $150,000 to provide supplemental support to Project 4, as described in Chapter 1. Reclamation continued its independent funding of Project 1 concerning water quality in Lake Powell.

Budget allocations in FY16 and FY17

In FY16, five projects related to native fish research are likely to be funded by the same Native Fish Conservation Contingency Fund that will support some projects in FY15. Three projects are not proposed for funding at this time due to inadequate budget support, and these projects are identified as "unfunded at this time." All other projects will be funded at 93% of the full budget request that is described at the end of each Project Description and in the appendices. The GCMRC staff will work with their research teams and their collaborators to identify ways to achieve 7% reduction in expenditures, and the GCMRC is confident that all work items identified as "funded" in FY16 will be completed despite only be supported at this reduced level. In FY17, the GCMRC does not proposed allocations from the Native Fish Conservation Contingency Fund, because uncertainty about the need to implement non-native fish control in out years becomes too great and the need to ensure adequate funding exists if action is triggered. The GCMRC proposes to fund projects at 95% of the full budget requests, and the GCMRC leadership will work with its staff and collaborators to identify ways to save the required 5% reduction in costs. Additionally, the GCMRC intends to aggressively seek supplemental funding to support continuation of research projects that are best continued for three years but for which only two years of funding are presently identified.

Triennial Work Plan Summary

The FY15–17 TWP is organized into 15 projects. Four projects are in the geophysical sciences: reservoir water quality monitoring (Project 1), sediment-transport/water-quality/stream-flow measurement (TWP Project 2), geomorphology of the active channel (TWP Project 3), and geomorphic processes affecting cultural resources in the Colorado River valley above the active channel (TWP Project 4). Six projects are in the fields of aquatic and fish ecology. These projects focus on the ecology of the food base (TWP Project 5), monitoring and research related to main-stem native and nonnative fish populations (TWP Project 6), humpback chub populations in the Little Colorado River (TWP Project 7), management actions designed to benefit native fish (TWP Project 8), rainbow trout in Glen and Marble Canyons (TWP Project 9), and evolving channel characteristics that affect fish habitat of the Glen Canyon Dam tailwater (TWP Project 10). TWP Project 5 comprises both new elements and elements from several different projects from the FY13–14 BWP. TWP Project 10 is new. Although food base studies were part of the GCMRC program in FY13–14, emerging results concerning the lack of species diversity, food-limited nature of the fishery, strong stakeholder interest, and strong interest among some sister agencies inspired GCMRC to significantly expand its proposed body of work. TWP Project 10 was developed in response to stakeholder interest in understanding the relationship between reservoir releases and associated changes in substrate and other attributes of physical habitat that provide advantage, and disadvantage, to rainbow trout populations in Glen, Marble, and eastern Grand Canyons. Two projects focus on vegetation. TWP Project 11 is a broad monitoring and research project focused on riparian and upland vegetation as well as linkages between the aquatic ecosystem and terrestrial fauna, and TWP Project 12 is designed to specifically examine changes in the distribution of some riparian and upland plants that are of specific interest to tribes. Socioeconomic studies are proposed in TWP Project 13 – a new effort on the part of GCMRC. Geographic information science, services, and support are described in TWP Project 14, and administrative and support activities are described in TWP Project 15.

Reservoir water quality, sediment-transport/water-quality/stream-flow measurement, geomorphology of the active channel, and geomorphology of the Colorado River valley above the active channel

Project 1 (called Project C in the FY13–14 BWP) is funded directly by Reclamation's Water Quality Program and received no funds from the GCDAMP in FY13–14. In FY15, GCMRC proposes to fund a Science Review Panel to evaluate past studies of reservoir physical limnology and ecology that have focused on Lakes Powell and Mead. This Panel will be asked to make recommendations to the GCDAMP, Reclamation, and to other relevant agencies on how reservoir limnology and ecology ought to be monitored in the future and to make recommendations about how existing and new modeling tools could be used to predict future conditions in Lake Powell. Water quality, including temperature, is a strong determinant of ecological processes in the CRe. Because GCMRC and Reclamation continue to discuss changes in the approach and data analysis needs of Project 1, and because that project is funded on a calendar year cycle independent from the federal fiscal year cycle of the GCDAMP, a preliminary description of Project 1 is included as Appendix 1 of this TWP.

TWP Project 2 (called Project B in the FY13–14 Work Plan) describes the monitoring program that measures the rate and quantity of the Colorado River's stream flow, as well as the water inflow that occurs from tributaries. Additionally, TWP Project 2 describes the measurement program of the fine sediment that enters the Colorado River from tributaries and measurement of the quality of the Colorado River's water. This project began as fundamental research in the late 1990s. In 2007, the TWG provided preliminary approval of this work as a GCDAMP core-monitoring project, designed to fully address the monitoring needs of GCDAMP Goal 7. This project has changed little since that time; two gages have been established on Kanab Creek and Havasu Creek that are partly funded by other USGS programs. The GCMRC considers TWP Project 2 to be a core-monitoring activity with a relatively small amount of associated data analysis and interpretation. In FY15–16 and as explained in the project proposal, the focus of this interpretative data analysis will be on the history of changing sediment delivery from the Paria and Little Colorado Rivers, because these two tributaries are the primary sources of fine sediment to the CRe.

TWP Project 3 (called Project A in the FY13–14 Work Plan) concerns the geomorphology of fine sediment deposits in the active channel of the Colorado River. Fine sediment is sand (0.0625 – 2 mm) and mud; in turn, mud is silt (0.0039-0.0625 mm) and clay (<0.0039 mm). These deposits are the substrate of the campsite resource, substrate in which the riparian ecosystem has developed, the architecture of shoreline aquatic habitat, and is the substrate in and on which archaeological sites occur. The existence of Glen Canyon Dam and Lake Powell causes the deposition of all of the fine sediment supplied from the Upper Colorado River basin in the reservoir. Releases of reservoir water at the dam are free of sediment, and there is only a small amount of fine sediment supply to Glen Canyon. The Paria River enters the Colorado River at Lees Ferry and delivers approximately 3.3×10^6 tons/yr of fine sediment (Topping et al., 2000), although the amount supplied from year to year varies greatly. The post-dam fine sediment supply to the upstream end of Marble Canyon has been decreased by 95%, in relation to the pre-dam fine sediment supply rate of 62.8×10^6 tons/yr that was supplied from the Upper Colorado River basin (Topping et al., 2000). Thus, the post-dam Colorado River has excess mechanical energy available to transport fine sediment, and large amounts of fine sediment on the river bed and in eddies has been eroded and transported downstream towards Lake Mead.

The remaining fine sediment deposits that are of greatest interest to river managers are primarily composed of sand and occur in eddies. Eddies typically occur downstream from the rapids that make Marble and Grand Canyons a famous recreational whitewater river. Since the 1970s, river scientists have struggled to understand the dynamics of the post-dam Colorado River and its adjustment to a greatly reduced fine sediment supply (Laursen and others, 1976, Howard and Dolan, 1981, Schmidt and Grams, 2011). It is inevitable that post-dam fine sediment deposits will be smaller and more sparsely distributed than pre-dam deposits, and significant river management questions concerning the Colorado River downstream from Glen Canyon Dam are:

> *What is the largest, sustainable amount of fine sediment that can occur along the banks of the Colorado River, especially as eddy sandbars? What flow regime, in relation to the natural supply of fine sediment from the Paria and Little Colorado Rivers, results in the most widespread distribution of fine sediment along the channel banks and in eddies?*

Similar questions have been asked as Strategic Science Questions and as information needs in various GCMRC and GCDAMP planning documents that were written in the 2000s. TWP Projects 2 and 3 explicitly follow on monitoring strategies that were proposed as core monitoring in the 2000s for Goal 7 and Goal 8, respectively, and are described in the CMP. TWP Projects 2 and 3 are essential to implement the HFE Protocol, because the Protocol calls for high flow releases from Glen Canyon Dam whenever a specified minimum amount of fine sediment delivered from the Paria River is exceeded. TWP Projects 2 and 3 are also responsive to the Assistant Secretary's directions provided in her 2011 and 2014 memos. TWP Project 2 is the measurement program needed to implement the HFE Protocol. TWP Project 3 supports the direct measurements of the volume of fine sediment, especially sand, that is stored on the bed of the Colorado River, in its eddies, or at higher elevation along the river's banks; these measurements allow assessment of the effectiveness of the Protocol. A significant accomplishment of these programs in FY13–14 was the development of web-based interfaces to serve sediment transport and water quality data, calculate fine sediment mass balances, and to serve photographs of approximately 50 sandbars. The latter data allow stakeholders to evaluate the effects of controlled floods implemented under the HFE Protocol.

TWP Project 4 (called Project J in the FY13–14 Work Plan) is focused on monitoring and research concerning geomorphic and weather processes that affect cultural resources above the active channel of the Colorado River. This project is responsive to Assistant Secretary Castle's guidance in her May 2014 memo and seeks to address longstanding issues associated with monitoring of landscape change near archaeological sites and other culturally significant properties. This project has been developed in collaboration with Reclamation in hopes that the proposed monitoring and research is responsive to agency needs. The project has also been reviewed by tribal representatives. Reclamation is providing supplemental budget support to this project.

Each of these projects has direct linkage to the DFCs. Project 1 and TWP Project 2 address the issues raised by the sediment and water quality elements of the CRe DFC that calls for attainment of dissolved oxygen, nutrient concentrations and cycling, turbidity, temperature, and hydro-physical conditions that support critical ecosystem functions. TWP Project 1 focuses on measurement of water quality attributes of Lake Powell reservoir while TWP Project 2 pertains to water quality, discharge, and sediment transport in the Colorado River and selected tributaries downstream of Glen Canyon Dam. TWP Project 3 addresses monitoring and research topics related to the sediment-related goals of the CRe, recreation and cultural DFCs – primarily the characteristics of near-shore habitats for native fish, the substrate characteristics and landforms associated with marsh and riparian habitat for fish, archaeological sites and camping beaches. TWP Project 4 addresses the linkage between fine-sediment deposits and cultural resource preservation that are articulated in the cultural resources DFC.

Projects in aquatic and fish ecology

TWP Projects 5, 6, 7, 8, 9, and 10 concern the fishes of the Colorado River and its tributaries, the food base on which those fish depend, and the habitats in which the food base and fishes occur. TWP Project 5 is a new stand-alone effort designed to continue monitoring of the aquatic food base and to conduct research to resolve questions about the current condition of the aquatic invertebrate community in Glen Canyon. Many of the research and monitoring projects on native and nonnative fish in the mainstem Colorado River are included in TWP Project 6. TWP Project

7 is a research project intended to resolve critical uncertainties about humpback chub and their life history in the Little Colorado River and near its confluence with the mainstem Colorado River. Experimental management treatments focused on benefitting native and nonnative fish are included in TWP Project 8 as is a proposed review of the fisheries program by an external protocol evaluation panel (PEP). TWP Project 9 concerns the rainbow trout fishery of Glen Canyon as well as the factors influencing the distribution and movement of rainbow trout in Marble Canyon. TWP Project 10 focuses on improving understanding of the relationships between physical habitat in Glen Canyon and Marble Canyon and rainbow trout recruitment and distribution.

The goals in developing the aquatic ecology and fisheries portions of the FY15–17 TWP were to continue long-term, core monitoring of key aquatic resources in the CRe while also looking to minimize redundancy and increase efficiency and to continue addressing persistent scientific uncertainties that have posed challenges to management of the aquatic ecosystem. Because nonnative rainbow and brown trout compete with and prey upon native fish, including humpback chub, the significant management question continues to focus on

> *What management strategies should to be employed to maintain a high quality rainbow trout fishery in Glen Canyon while protecting, and potentially recovering, the endangered humpback chub and related native fish community in Marble and Grand Canyons?*

New or expanded research projects are intended to provide information in areas where the greatest uncertainty remains. Most of the monitoring needs in the FY15–17 TWP were identified in the Environmental Assessment for Non-Native Fish Control Downstream from Glen Canyon Dam and its associated Biological Opinion. These documents also identified areas of uncertainty where more research was needed. These uncertainties, as well as others identified during interactions with stakeholders, informal meetings among scientists from cooperating agencies, and meetings organized as part of the development of the LTEMP EIS formed the foundation of the projects for new and expanded research presented in the TWP.

Monitoring of the aquatic food base and research of the biology and ecology of the aquatic invertebrates that comprise this important resource will continue or be expanded. Information to be collected in Glen, Marble, and Grand Canyons as part of TWP Project 5 includes production of algae and invertebrates, organic matter biomass, drift of invertebrates and organic matter, and the abundance, distribution, and timing of emergence of flying insects. New research to understand the lack of aquatic invertebrate diversity in Glen Canyon will also be conducted including laboratory experimentation and field observation of how insect reproduction, egg survival, and emergence is influenced by various temperature and flow conditions. Supplemental funding external to the GCDAMP is also being sought to support a comparative study of the CRe aquatic food base with other western U.S. tailwaters. Understanding the aquatic food base and how dam operations and other factors influence its dynamics are essential to understanding the distribution, condition, and abundance of fish populations in the CRe.

The emphasis of research proposed in other projects is on native fish, especially humpback chub, and nonnative fish that potentially threaten the recovery of this endangered species. Although much has been learned about the distribution, habitat use, life history, population dynamics, and other aspects of the biology and ecology of this species, key uncertainties remain. Two areas of uncertainty believed to be among the most critical include the dynamics and ecology of the groups of humpback chub known as aggregations that live in discrete areas of the mainstem Colorado River (TWP Project 6) and the variability in survival, growth, and emigration rates of early life history stages of humpback chub in the Little Colorado River. Additionally, little is known about the physical and biological drivers of this variation (TWP Project 7). Interactions between native and nonnative fish, particularly between humpback chub and trout, are still an area of concern. Continued laboratory experimentation and field study is needed to better understand the predation and competition effects of nonnative fish on native species and to determine to what extent these interactions are affected by environmental conditions (TWP Project 7).

Several management actions designed to increase survival of juvenile native fishes in the CRe will continue or begin during FY15–17. Mechanical removal of rainbow trout and brown trout near the confluence of Bright Angel Creek will continue in cooperation with the National Park Service in support of their efforts to restore native fish to this perennial tributary. Translocations of juvenile humpback chub from the Little Colorado River into unoccupied areas within this river will continue as will support of National Park Service translocation efforts into Havasu Creek and Shinumo Creek. New activities include an assessment of potentially harmful aquatic species within the Little Colorado River and genetic monitoring of humpback chub to confirm that ongoing management activities are not having negative effects. Finally, a review of the GCDAMP fisheries program will be conducted by an external review panel or PEP comprised of scientists with expertise relevant to ongoing research and monitoring activities. Maintaining the rainbow trout fishery in Glen Canyon has been a longstanding management priority. While our understanding of some of the drivers of this population has improved, a number of unknowns remain including a full understanding of the effects of flow-related actions like the seasonal timing of HFEs and dam releases to achieve equalization of reservoir storage volumes. A combination of laboratory and field studies, modeling, and comparison to similar systems will help clarify the drivers of rainbow trout population status and trends, size composition, and downstream migration (TWP Project 9), thus allowing for more effective management of this important tailwater fishery that is an element of the recreation DFC.

Monitoring of key aquatic resources in the CRe remains a critical component of the FY15–17 TWP. These projects generate data that can be used to provide a baseline for observing status and trends in resources of interest, to assess the effectiveness of various management actions, and to inform managers as to the need to conduct management actions or the attainment of identified goals. Surveys of humpback chub and other fishes are proposed to continue in the Little Colorado River (TWP Project 7). This will include both physical captures of fish in the spring and fall and continuous electronic monitoring to detect individuals previously tagged with passive integrated transponders. Mainstem surveys of native and nonnative fish will also continue annually in the spring and fall as part of Project 6 and quarterly near the mouth of the Little Colorado River (TWP Projects 7 and 9) to gather information on young humpback chub and trout. These surveys provide critical information on triggers for potential management actions to control nonnative fish abundance identified in the Biological Opinion for the HFE and nonnative fish control EAs. Needed information includes survival rates of young humpback chub, the relative abundance of sub-adult and adult humpback chub, and trout abundance near the Little Colorado River confluence. Additional monitoring activities include surveys of trout spawning, early life stages, and adult populations in Glen Canyon, trout abundance and emigration in Marble Canyon, and the distributions and relative abundance of all native and nonnative fishes in Glen, Marble, and Grand Canyons. These efforts will help keep scientists and managers informed on the status and trends of fish throughout the CRe and will provide a mechanism of surveillance and early detection of invasive fish species.

The CRe DFC for the aquatic domain focuses on desired attributes of native species, rainbow trout, extirpated species, and non-fish biotic communities. TWP Projects 6, 7, and 8 are focused on native fish species, especially the humpback chub, a federally-listed endangered species. Monitoring and research activities in TWP Projects 6 and 7 address scientific issues associated with the desired recovery of humpback chub throughout its former range in the CRe. TWP Project 7 is focused on scientific issues associated with the largest aggregation of humpback chub that occurs in and near the Little Colorado River. Project 8 entails management actions designed to benefit native fish. TWP Project 9 is focused on rainbow trout in Glen and Marble Canyons, and TWP Project 9.6 is focused on the interactions between trout and native fish throughout the CRe. There are no proposed projects that focus on the re-establishment of extirpated fish species in the CRe, despite the stated DFC element on this topic. There are also no proposed projects focused on nonnative non-fish species such as the Northern Leopard Frog, although TWP Project 5 does include characterization of the invertebrate community that is a key part of the food base for native and nonnative fish.

Projects in riparian ecology

TWP Project 11 (called Project I in the FY13–14 Work Plan) builds on the plant-response guild research and monitoring conducted in the FY13–14 Work Plan to further stakeholder understanding of the role of riparian vegetation in ecosystem processes in a regulated river ecosystem. The project includes a continuation of the ground-based and landscape scale monitoring approaches initiated in FY13. The ground-based sampling downstream of Glen Canyon Dam is complimentary to riparian monitoring data that are collected within other National Park Service units in the Upper Colorado River Basin by their Inventory and Monitoring Program. The landscape scale monitoring is moving from the total vegetation change analysis conducted in FY13–14 to the specific change analysis of vegetation classes and comparison of changes among river segments and different depositional environments (sandbars, debris fans, channel margins). Information gained in TWP Project 11 monitoring supports efforts in TWP Project 3 that endeavor to understand sediment dynamics over time and particularly with regard to sediment response and the HFE Protocol.

With the increasing recognition of the role that both vegetation and river regulation have on fluvial geomorphology, studies evaluating the additive effects of these ecosystem drivers on shoreline and channel geomorphic landforms are increasingly relevant. Research elements in TWP Project 11 will utilize the plant-response guilds to probabilistically evaluate and assess wildlife habitat, and integrate the response guilds with a 22-year topographic survey record for retrospective analyses of topographic change of 20 sandbars. A retrospective analysis of sandbar evolution contributes to an understanding of how landforms along the channel change in response to annual hydrology, controlled floods, and the presence of vegetation. In this regard, TWP Project 11 is linked to the research priority for sediment identified by the Assistant Secretary in her 2011 and 2014 memos. Increasing our knowledge about plant responses to changing hydrology can also support resource managers' concerns about management of nonnative plants that may or may not benefit from changes in future flow regimes or how flow regimes might be integrated into decisions regarding plant removal and restoration. TWP Project Element 11.5 is intended to begin to address these questions.

Collectively, the monitoring and research proposed in TWP Project 11 supports the GCDAMP's efforts to evaluate the HFE Protocol (Bureau of Reclamation, 2011a) and flow alternatives that will result from the on-going LTEMP EIS. The proposed research elements fundamentally aid in furthering our understanding of the role of riparian vegetation in ecosystem processes of a regulated river.

TWP Project 11 is focused on the CRe riparian domain. This project is primarily a vegetation monitoring project, because the distribution of vegetation communities, characterized as vegetation response guilds, and the distribution of fine-sediment substrates constitutes the various riparian habitats that are of interest in the DFCs. This project also includes an element to explore the linkages between the aquatic ecosystem and terrestrial fauna, especially insects and insectivores.

Cultural resources monitoring and research project

The cultural resources program continues to be a significant focus of GCMRC activity in FY15–17. TWP Project 4 explicitly focuses on providing scientific support for agency management responsibilities, especially regarding development of a new Programmatic Agreement and in relation to monitoring responsibilities associated with the HFE Protocol. Reclamation is independently providing $150,000 to support this work in FY15 and FY16 and slightly more support in FY17. This project involves a research component that follows on work completed by Amy Draut East, Brian Collins, Joel Sankey, and others in FY13–14. The other part of this project involves development of a formal archaeological site monitoring program that builds on work completed by Brian Collins, Helen Fairley, and others since 2009 and would be implemented in FY16. TWP Project 12 is a small and novel project to evaluate historical changes in the distribution of plants significant to tribes, and some tribes are formally cooperating in this effort.

Cultural resources in the CRe include prehistoric archaeological sites, historic sites, and TCPs that are eligible for listing on the National Register of Historic Places (NRHP) as well as culturally-valued plants, animals and landscapes that are not individually eligible for listing on the NRHP. The primary DFC objective for prehistoric archaeological sites and for historic sites is “to the extent feasible, maintain significance and integrity through preservation in place” while the primary objective for TCPs is that they are maintained such that National Register eligibility is not compromised. The DFC objectives for non-NRHP eligible cultural resources are similar in that they strive to “maintain culturally appropriate resource conditions based on traditional ecological knowledge and integrate this desired condition into monitoring and management programs.” Thus, the DFCs for cultural resources recognize that many natural processes and attributes of the CRe affect cultural resources. These processes include those related to stream flow, sediment transport, geomorphology, and riparian vegetation. Cultural resources are also affected by recreation activity. The DFC specifically proposes that achievement of the goals for cultural resources be measured by:

Erosion or deposition rates of substrates in which cultural sites occur
Impacts at sites that affect eligibility to the National Register of Historic Places

The FY15–17 TWP is responsive to these DFCs and their proposed metrics. TWP Project 11 involves a system-wide monitoring of riparian vegetation. TWP Project 4.1 continues a system-wide, comprehensive study of geomorphic processes and geomorphic attributes that affect prehistoric and historic sites. Such a project has never been previously undertaken as part of the GCDAMP-funded GCMRC program. The goal of this project is to establish the linkage between the area and abundance of river sandbars (TWP Project 3) that are directly affected by dam operations and the redistribution of fine sediment upslope to areas that contain prehistoric and historic sites. Additionally, Project 4 evaluates the degree to which gullies in the CRe grow or are eliminated by changing geomorphic conditions in the river channel itself. This Project also applies detailed measurement protocols in Glen, Marble, and Grand Canyons to precisely measure topographic changes at the local scale. The challenge of TWP Project 4 is to provide scientific guidance as to how large-scale and local-scale measurements and observations can be linked.

The cultural resource DFCs also propose metrics for assessing the condition of resources other than archaeological and historic sites that are traditionally valued by Native American tribes and other communities. Because “only members of that culture can assess the status or health of the [TCP] resources” important to each Native American Tribe, TCP monitoring activities are not part of the GCMRC program. Tribes are funded directly for their monitoring efforts, as described in Chapter 1. However, in the FY15–17 TWP, a small and novel project is proposed to evaluate historical changes in the distribution of plants significant to tribes and through doing this evaluation, to elucidate the linkages between changes in vegetation and effects to traditional tribal cultural values associated with the riparian landscape. Some tribes are formally cooperating in this effort. Relevant vegetation data from TWP Project 11 will be incorporated into TWP Project 12.

Socioeconomic project

TWP Project 13 initiates socioeconomic monitoring and research at GCMRC. This project will identify recreational user and tribal preferences for, and values of, downstream resources and evaluate how they are influenced by operations at Glen Canyon Dam. In addition, the project will integrate economic information with data from long-term and ongoing physical and biological monitoring and research studies led by GCMRC to develop a decision support system that will improve the ability of the GCDAMP to evaluate and prioritize management actions, monitoring and research. Specifically, the project involves three related socioeconomic monitoring and research studies that include: (a) evaluation of the impact of Glen Canyon Dam operations on regional economic expenditures and economic values associated with angling in Glen Canyon National Recreation Area downstream from Glen Canyon Dam, and whitewater boating in Grand Canyon National Park that begins at Lees Ferry; (b) assessment of the impact of Glen Canyon Dam operations on tribal preference for, and value of, downstream resources; and (c) development of decision methods, using economic metrics, to evaluate management actions and prioritize monitoring and research on resources downstream of Glen Canyon Dam. The recreation economics research builds on work from the late 1980s, under the Glen Canyon Environmental Studies program, that established a relationship between dam operations and recreational economic values related to angling and whitewater boating. Carryover funding from FY13 has been allocated to initiate the recreation economics research in FY14. The recreation economics research will continue in FY15–16. The decision methods and tribal research, original research at GCMRC, will be initiated in FY15 and FY16, respectively, and continue into FY17.

The overarching DFC goal and objective for power is that “Glen Canyon Dam capacity and energy generation is maintained and increased, so as to produce the greatest practicable amount of power and energy, consistent with the other DFCs.” Thus, the DFC for power identifies the importance of hydropower to the greater Western Electricity Coordinating Council, but recognizes the influence that hydropeaking power production at Glen Canyon Dam can have on other downstream resources. TWP Project 13 contributes to discussion about tradeoffs between natural and economic values by initiating development of a decision support system to inform the GCDAMP in the organization and evaluation of management actions, monitoring, and research. The analytical methods, predictive models in the decision support system, will provide a platform to identify the least-cost approach (i.e., foregone hydropower) to meet other DFCs. The research in TWP Project 13 is consistent with the goal and objective of the power DFC and with the Record of Decision's goal of not maximizing benefits but determining an operation at Glen Canyon Dam that limits impact to hydropower while meeting recovery and long-term sustainability of downstream resources.

There are four categories for recreation DFCs: 1) river recreation in Grand Canyon National Park; 2) river recreation in Glen Canyon National Recreation Area; 3) blue ribbon trout fishery in Glen Canyon National Recreation Area; and 4) river corridor stewardship. Each category identifies specific resource conditions as goals and objectives. The metrics used to evaluate these goals and objectives include the condition of recreational resources, socioeconomic value associated with the recreation, and overall recreation visitation/expenditures. The FY15–17 TWP will provide monitoring and research concerning the socioeconomic value of river recreation and angling below Glen Canyon Dam (TWP Project 13). This research will also inform on the preference for resource quality and the regional economic effects of recreation based tourism in Glen Canyon National Recreation Area and Grand Canyon National Park. This information provides a subset of the metrics proposed to evaluate recreation DFCs. As described above, TWP Project 13 also initiates the development of a decision support system to inform the GCDAMP in the organization and evaluation of management actions, monitoring, and research. This will allow GCDAMP to better evaluate the tradeoffs, how the recreation metrics in the DFCs are impacted, among other resource DFCs when managing the operation of Glen Canyon Dam.

The FY15–17 TWP will also provide monitoring data concerning other recreation DFCs and the metrics used to evaluate them. The distribution and size of campable beaches is an element of TWP Project 3. Additionally, TWP Project 7 will provide research and monitoring data concerning the interactions between trout and native fish and TWP Project 9 will directly inform management of the Glen Canyon tailwater fishery. A creel survey (TWP Project 6.8) will also provide data concerning angler success and experience in GCNRA.

Geographic information systems (GIS), services, and support

TWP Project 14 concerns the implementation of GIS support both in terms of direct involvement in proposed science work (TWP Projects 3, 4, 5, 6, 7, 9 and 10), and as a stand-alone effort that performs many functions within GCMRC and GCDAMP. These functions include the ability to serve as the focal point of geospatial knowledge and application, fulfill the role of geospatial data management, further develop GIS as a vehicle for data integration, and provide a gateway into GCMRC's collection of geospatial data holdings.

Independent review and science oversight

In FY15 and FY16, GCMRC proposes to convene three science oversight and review panels. One of these panels will focus on reservoir limnology and ecology, because the characteristics of Lake Powell will determine the long-term characteristics of the CRe. At the downstream end of the ecosystem, the limnology of Lake Mead is occasionally determined by inflows from controlled floods. Navigation across the emergent delta of Lake Mead is strongly affected by the storage contents of the reservoir. GCMRC is committed to working with Reclamation to identify a robust monitoring and research program that can aid in making future decisions about water management of these two large reservoirs.

Significant effort was expended in spring 2014 in developing the native fish and rainbow trout monitoring programs. These programs are implemented by a consortium of GCMRC, Arizona

Game and Fish Department, US Fish and Wildlife Service, National Park Service, and cooperators. Although progress was made in developing an efficient and cost-effective program, much remains to be done to hone this program to meet the science needs of the GCDAMP while also expending money efficiently. We believe that a panel of science experts on this topic could greatly assist the agencies in developing this program for the future.

In early June, 2014, GCMRC was notified that riparian vegetation management was being proposed for the CRe. This work would be part of the LTEMP EIS program. Following conversation with sister agencies, GCMRC added an element to TWP Project 11 and will conduct a science panel to review methods of riparian vegetation management and monitoring in an effort to provide stakeholders and the National Park Service with a scientific basis to initiate this program.

Table 3. Independent review and science oversight components of the FY15/16/17 TWP

1.2	Reservoir limnology and ecology monitoring and research science review panel	$21,000 (FY15)
8.3	Fisheries Protocol Evaluation Panel	$21,000 (FY16)
11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	$34,000 (FY15)

GCMRC project administration

Administration of the GCMRCs work is funded in two ways – as direct costs associated with the salaries and travel expenses of key leadership and administrative personnel and as indirect costs (called "burden" in the USGS) that support the USGS Southwest Biological Science Center (SBSC). Part of the indirect costs are assessed at a 16% burden rate in FY15 on all work conducted by GCMRC staff and partly by a direct $1 million allocation by the USGS to the SBSC. The burden rate increases to 22% in FY16 and to 28% in FY17.

Allocation of the FY15–17 Budget

The total recommended budget of GCMRC in FY2015 is $9.5 million. Funding for this amount includes $8.7 million from GCDAMP funds and an additional $0.8 million from other Reclamation funding sources, including $0.4 million for native fish projects from the Native Fish Conservation Contingency Fund.

Of the approximate $9.5 million recommended budget for FY15, 40% is to be allocated to monitoring and research work in aquatic ecology and fisheries and 31% is to be allocated to the projects in geomorphology, stream flow monitoring, sediment transport, and water quality. Direct GCMRC administrative costs are 14% of the budget. The combined work in riparian ecology, cultural resources, economics, and independent reviews is a small proportion of the proposed work. The budget for the GCMRC part of the FY15–17 TWP is described at the end of each project description, and is summarized in various appendices at the end of this document. The total recommended budget of GCMRC in FY2016 is $9.9 million. Funding for this amount includes $9.0 million from GCDAMP funds, $0.1 million from anticipated GCMRC carryover funds, and an additional $0.7 million from other Reclamation funding sources, including $0.3 million for native fish projects from the Native Fish Conservation Contingency Fund.

The total recommended budget of GCMRC in FY2017 is $9.8 million. Funding for this amount includes $9.3 million from GCDAMP funds and an additional $0.5 million from other Reclamation funding sources.

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Project 2. Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem

Initial Estimate: FY15: $1,340,300; FY16: $1,452,000; FY17: $1,534.900

GCDAMP Funding: FY15: $1,343,300; FY16: $1,350,400; FY17: $1,458,200

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B. Project Summary

This project makes the basic measurements that link dam operations and reservoir releases to the physical, biological, and sociocultural resources of the Colorado River ecosystem (CRe) downstream from Glen Canyon Dam. This project conducts the monitoring of stage, discharge, water quality (water temperature, specific conductance, turbidity, dissolved oxygen), suspended sediment, and bed sediment. Measurements are made at gaging stations located in Glen Canyon National Recreation Area, Grand Canyon National Park, the Navajo Reservation, and the Hualapai Reservation and on lands administered by the Bureau of Land Management. The data collected by this project provide the stream-flow, sediment-transport, sediment-mass-balance, water-temperature, and water-quality data that are required to link dam operations with the status of the CRe. In addition, the data collected by this project are used to implement and evaluate the High Flow Experiment (HFE) Protocol and in evaluations of alternatives being assessed by the Long-Term Experimental and Management Plan (LTEMP) EIS. The data collected by this project are also used in other physical, ecological, and socio-cultural projects described elsewhere in this Triennial Work Plan. Other project funds support interpretation of basic data.

C. Background

C.1. Scientific Background

The primary linkage between the release of Lake Powell reservoir water and the characteristics of the physical, biological, and cultural resources of the CRe is through the stage, discharge, water quality, and sediment transport of the Colorado River (Gloss and others, 2005). Reservoir releases are the principal determinant of the Colorado River's flow regime, sediment supply, sediment-transport regime, and temperature regime, because tributary inflows only affect the Colorado River's characteristics during rare, large tributary floods (Topping and others, 2000a, 2000b; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010a, 2014).

Although there are short reaches of the river corridor where the bed and banks are bedrock, unconsolidated sediment on the bed and banks constitutes the physical template of most of the CRe, (Gloss and others, 2005; Melis, 2011). Although some parts of the river corridor are composed of coarse sediments derived from hillslope processes, most of the bed and banks of the Colorado River are composed of coarse and fine sediment occasionally or frequently transported by the Colorado River. Hereafter, these sediments are termed main-stem alluvial sediments. Most of the main-stem alluvial sediments transported by the Colorado River are fine grained, meaning that they are less than 2 mm in diameter -- sand, silt, and clay. Coarse, main-stem alluvial sediment—gravel, cobbles, and boulders—is occasionally transported by the Colorado River.

Most of the fine sediment is transported in suspension, although small amounts are transported as bedload (Rubin and others, 2001). This project is primarily focused on the measurement of suspended, fine-grain-sediment transport. A small research project element that is part of Project 3 (Project element 3.4) concerns refining previous estimates (Rubin and others, 2001) of the proportion of the total fine sediment flux that is transported as bedload.

Suspended sediment is an important water quality parameter, because the accumulation or evacuation of fine sediment determines whether eddy sandbars and channel-margin deposits aggrade or are eroded; these types of topographic changes are important to many biological, cultural, and recreational resources (Rubin and others, 2002, Wright and others, 2005, 2008). Suspended sediment transport also controls turbidity, and therefore influences the aquatic and fish ecology of the river. The endemic fishes of the CRe evolved in a highly turbid river (Gloss and Coggins, 2005).

Turbidity is predominantly determined by the concentration of suspended silt and clay (hereafter called mud) and, to a lesser degree, suspended sand (Voichick and Topping, 2014). Prior to closure of Glen Canyon Dam, 60% of the fine sediment supply to the upstream end of the CRe was mud (Topping and others, 2000a). Closure of Glen Canyon Dam reduced the supply of sand and mud by about 95% at Lees Ferry, and the Paria River is now the major supplier of fine sediment to Marble Canyon (Topping and others, 2000a, 2000b). The post-dam Colorado River in Marble and Grand Canyons is much less turbid than ever occurred naturally (Voichick and Topping, 2014). Because the in-channel storage of sand and mud in the post-dam Colorado River is greatly reduced from pre-dam conditions, the Colorado River in the CRe is only now turbid during periods of tributary flooding.

Fine-sediment deposits that occur within the active channel of the Colorado River are primarily composed of sand. Sand fills some deep pools in the channel and occurs elsewhere as discrete patches (Anima and others, 1998; Schmidt and others, 2007; Grams and others, 2013). Mapping of the distribution of sand and mud on the channel bed occurs as part of Project Element 3.2. Eddy sandbars occur along the margins of the active channel, and channel-margin deposits occur as discrete patches of floodplain in wider parts of Glen, Marble, and Grand Canyons (Schmidt, 1990; Schmidt and Graf, 1990). Higher deposits of fine sediment that typically are composed of larger proportions of mud and very fine sand occur as alluvial terraces above the modern active channel. These pre-dam terraces were formed by floods that no longer occur. Even higher above the active channel are dunes and other fine-sediment wind deposits that are the subject of monitoring and research described in Project 4.

The long-term fate of all sand deposits in and near the Colorado River in the CRe is determined by the capacity of the main stem to transport those sediments downstream to Lake Mead reservoir in relation to the rate at which similar size sediment is supplied by the Paria River, Little Colorado River, and smaller tributaries. Measurements of suspended sediment transport and combined with stream-flow measurements are used to calculate the total mass of fine sediment entering or leaving segments of the Colorado River. The difference between the mass entering and leaving a river segment is termed "mass balance," and calculations of mass balance are made by this project.Systematic measurements of stream flow and the quality of water, including suspended-sediment concentration, in the CRe began with installation of the Lees Ferry gaging station (USGS gaging station 09380000, Colorado River at Lees Ferry, AZ) in May 1921 (Howard, 1947; Topping and others, 2003). During much of the 20th century, daily measurements of suspended-sediment concentration and temperature, and episodic measurements of other water-quality parameters, were made by the USGS throughout the Colorado River basin. This intensive period of measurements ended in the early 1970s (Andrews, 1991; Topping and others, 2000a). Concern about the effects of operations of Glen Canyon Dam on the CRe resulted in a new emphasis on scientific measurements and modeling of water quality and sediment transport beginning in the early 1980s (National Research Council, 1996). The results of these studies have been published in numerous USGS reports and journal articles, and ultimately resulted in the current form of the proposed project.

Recent research on the Colorado and on other rivers has shown that, to be meaningful, measurements of stage, discharge, water quality, and suspended sediment must be made at temporal resolutions higher than those over which these parameters vary. In the specific case of suspended sediment, substantial changes in suspended-sand concentration and suspended-mud concentration are determined by changes in the upstream supply of those sediments. These changes typically occur over timescales less than 1 hour (Topping and others, 2000b; Wright and others, 2010a, 2010b). Furthermore, Rubin and Topping (2001a, 2001b, 2008) showed that, in the case of the dam-regulated Colorado River, suspended-sand transport is co-equally regulated by changes in discharge and changes in the grain-size of sand available for transport that in turn is determined by the upstream supply of sand. The former control is largely determined by changes in dam operations, and the latter control is largely determined by changes in tributary sand supply. Topping and others (2005a, 2007a, 2010) showed that sand transport is much more sensitive to sand-supply-driven changes in the grain-size distribution of the bed sediment than by changes in the amount of sand covering the bed. Topping and others (2005b, 2008) and Hazel and others (2006) built on the work of Rubin and Topping and concluded that eddy sandbars are the dominant river environment containing sand. Therefore, these deposits are the primary regulators of sand transport in the Colorado River. These findings invalidated key assumptions of the 1995 EIS (U.S. Department of the Interior, 1995) that assumed that suspended-sand transport was only regulated by changes in discharge (Rubin and others, 2002).

This project is designed to provide measurements of stage, discharge, water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minute) to allow accurate determination of suspended sediment loads, as well as other water quality parameters. Collection of such data at 15-minute intervals is the USGS standard. Collection of data at the 15-minute temporal resolution is required to accurately describe the changes in stage, discharge, water quality, and sediment transport in the CRe that have been documented to occur at intervals << 1 hour (for example, Topping and others, 2000b; Voichick, 2008; Voichick and Topping, 2010a). Months to years of data collected at this resolution easily fit on standard dataloggers, result in no additional processing time in the office, and result in no additional financial cost to the project. In addition, because random error is reduced as $1/\sqrt{n}$, where n = number of samples, data collection at >>15-minute intervals would not only hamper detection of systematic changes in stage, discharge, water quality, and sediment transport, but would substantially increase the error in the measurements provided by this project.

To allow the construction of this comprehensive monitoring network, this project has conducted pioneering research on using laser-diffraction and acoustic technologies to measure water quality and sediment transport (Melis and others, 2003; Topping and others, 2004, 2006a, 2007b; Wright and others, 2010c; Voichick and Topping, 2010b, 2014; Griffiths and others, 2012). The acoustic technologies and methods developed by this project to measure sediment transport in the Colorado River are now being used in monitoring networks to inform river managers in and near Big Bend National Park, Dinosaur National Monument, and Canyonlands National Park.

The various continuous measurements, as well as episodic measurements of bed sediment, of the main-stem Colorado River are made at USGS stream-flow gaging stations located at river miles (RM) 0, 30, 61, 87, 166, and 225 (Griffiths and others, 2012). Selection of these gaging-station locations was largely based on the need to resolve longitudinal differences in sediment storage in key river segments that bracket major tributaries. Elsewhere, gage locations were established to support other GCDAMP-funded projects or to reoccupy former gaging stations. In addition, high-resolution stage, discharge, water temperature, suspended-sediment concentration, and suspended-sediment grain-size distribution are measured at sites in all of the major tributaries to the Colorado River and in a representative subset of the smaller, and formerly ungaged, tributaries (Griffiths and others, 2010, 2014).

All measurements of stage, discharge, water quality, and all physical measurements of suspended and bed sediment are made using standard, approved USGS techniques. Errors in conventional suspended-sediment measurements are calculated using the methods of Topping and others (2011) and Sabol and Topping (2013). The laser diffraction and acoustic measurements of suspended sediment are made using techniques described in Melis and others (2003), Topping and others (2004, 2006a, 2007b), and Wright and others (2010c).

The funding requested here only partially covers the costs of data collection at the USGS gaging stations, because operations of some of the gaging stations are supported by non-GCDAMP sources. Thus, gaging station locations are partially dictated by non-GCDAMP goals. For example, gage height and discharge data collected at the gaging stations on the Colorado River at Lees Ferry, AZ (station number 09380000), and above Diamond Creek near Peach Springs, AZ (09404200), are entirely funded from non-GCDAMP sources. In addition, gage height and discharge data collected at the gaging stations on the Paria River at Lees Ferry, AZ (09382000), the Little Colorado River near Cameron, AZ (09402000), and on the Colorado River near Grand Canyon, AZ (09402500), are significantly subsidized by non-GCDAMP sources. All of the personnel listed on this project receive parts of their salary from non-GCDAMP sources.

The most significant product from this project during FY 2013-14 was the development of the website on which we serve project data and serve user-interactive sediment budgets: http://www.gcmrc.gov/discharge_qw_sediment/. All database and website work has been made possible through collaboration with the USGS Center for Integrated Data Analytics (CIDA). The CIDA is the leader within the USGS in database and web programming. Collaboration with the CIDA has resulted in a major leap forward in serving data in a user friendly and interactive way, something that has proven problematic for GCMRC to do on its own in previous funding cycles.

The tools developed in collaboration with the CIDA are allowing anyone to plot the data, construct mass-balance sediment budgets, and plot changes in reach-averaged bed-sediment grain size for any time period in any reach of the CRe on demand. In addition, these tools allow different user-chosen methods for error propagation through these sediment budgets. Because sandbar response during controlled floods depends on both the amount and grain-size distribution of the sand stored in each river segment (Topping and others, 2006b, 2010), these tools have proven to be extremely useful in the planning of controlled floods under the HFE Protocol (U.S. Department of the Interior, 2011) and will inform future monitoring efforts.

C.2. Management Background

This project began as fundamental research in the late 1990s. Based on the scientific results described above, the project was recognized by the GCDAMP as a core-monitoring project in 2007. The project was designed to fully address the monitoring needs of GCDAMP Goal 7 (*Establish water temperature, quality, and flow dynamics to achieve GCDAMP ecosystem goals*) and to partially address the monitoring needs of GCDAMP Goal 8 (*Maintain or attain levels of sediment storage within the main channel and along shorelines to achieve GCDAMP ecosystem goals*). The primary objective of this project is to collect the basic monitoring data that directly link dam operations and reservoir releases to the physical template of the CRe.

In addition to supporting GCDAMP Goals 7 and 8, this project provides indirect support for Goals 1 (*Protect or improve the aquatic food base so that it will support viable populations of desired species at higher trophic levels*), 2 (*Maintain or attain a viable population of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats*), 4 (*Maintain a wild reproducing population of rainbow trout above the Paria River to the extent practicable and consistent with the maintenance of viable populations of native fish*), 6 (*Protect or improve the biotic riparian and spring communities within the CRe, including threatened and endangered species and their critical habitat*), 9 (*Maintain or improve the quality of recreational experiences for users of the CRe within the framework of GCDAMP ecosystem goals*), and 11 (*Preserve, protect, manage, and treat cultural resources for the inspiration and benefit of past, present, and future generations*).

Indirect support is provided by providing the basic stream-flow and water quality data that other scientists and stakeholders use to link dam operations to resource condition. This project supports Goal 1 by providing information on flows, water temperature, turbidity, and dissolved oxygen that aids in food base studies, such as the assessment of primary productivity and allochthonous inputs. This project supports Goal 2 by providing water-temperature data for the assessment of fish growth rates, turbidity data that are used to adjust for catch efficiency in population models, flow and stage data that are important to understanding the effects of near-shore habitat changes caused by fluctuating flows, and data on sandbars and resulting backwater habitats that are helpful in understanding the importance of sandbars for native fish. This project supports Goal 4 through monitoring of discharge, water temperature, specific conductance, turbidity, and dissolved oxygen conditions in Glen Canyon. This project supports Goal 6 by monitoring the transport and fate of sand and mud, which provides the substrate for riparian vegetation and marsh communities. This project supports Goal 9 by collecting the monitoring data used in experimental and modeling research relating flow and sediment-transport dynamics to the size and abundance of sandbars used as campsites. This project supports Goal 11 by collecting the stage, flow, and sediment data used to assess effects of dam operations on cultural sites.

The stream-flow and sediment-transport data collected by this project are required to trigger and evaluate the HFE Protocol (U.S. Department of the Interior, 2011). In addition, the stage, stream-flow, sediment-transport, sediment-budget, water-temperature, dissolved-oxygen, specific-conductance, and turbidity data collected by this project are used by other projects that seek to link the status of CRe resources with reservoir releases. The stream-flow, sediment transport, and water quality data are used to directly address several Desired Future Conditions (DFCs) (see Table 1, in Chapter 2 Introduction).The measurements made in this project are also indirectly used to interpret ecological patterns related to the aquatic foodbase, native fish, the Glen Canyon trout fishery, and the riparian zone. Data collected by this project not only constitute core monitoring but also supports other policy developments, such as the LTEMP EIS. Additionally, these data are used to monitor compliance with the 1996 Record of Decision that followed the 1995 EIS, supports research about flow experiments, and are critical to development of numerical models concerning river processes.

C.3. Monitoring and Research Questions Posed by Stakeholders that Are Addressed in This Project

This project provides direct support to some of the priority questions identified by the GCDAMP Adaptive Management Work Group in August 2004. Monitoring of stage, discharge, sediment transport, water temperature, and other water quality parameters directly supports some priority questions and indirectly supports other questions by providing information on the general physical framework of the riverine environment.

This project also directly addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) previously identified by the GCDAMP.

- **SSQ 4-1.** Is there a “Flow-Only” operation (that is, a strategy for dam releases, including managing tributary inputs with BHBFs, without sediment augmentation) that will restore and maintain sandbar habitats over decadal timescales?
- **SSQ 5-1.** How do dam release temperatures, flows (average and fluctuating component), meteorology, canyon orientation and geometry, and reach morphology interact to determine main-stem and near-shore water temperatures throughout the CRe?
- **CMIN 7.4.2.** Determine and track flow releases from Glen Canyon Dam, under all operating conditions, particularly related to flow duration, upramp, and downramp conditions.
- **CMIN 7.1.2.** Determine and track Little Colorado River discharge and temperature near the mouth.
- **CMIN 7.1.1.** Determine the water temperature dynamics in the main stem, tributaries backwaters, and near-shore areas throughout the CRe.
- **CMIN 8.1.3.** Track, as appropriate, the monthly sand and mud volumes and grain-size characteristics, by reach, as measured or estimated at the Paria and LCR, other major tributaries like Kanab and Havasu Creeks, and “lesser” tributaries?
- **CMIN 8.1.2.** What are the monthly sand and mud export volumes and grain-size characteristics, by reach, as measured or estimated at Lees Ferry, lower Marble Canyon, Grand Canyon, and Diamond Creek Stations?
- **RIN 7.4.1.** What is the desired range of seasonal and annual flow dynamics associated with power-plant operations, BHBFs, and habitat maintenance flows, or other flows that meet GCDAMP goals and objectives?

- **RIN 7.3.1.** Develop simulation models for Lake Powell and the Colorado River to predict water-quality conditions under various operating scenarios, supplant monitoring efforts, and elucidate understanding of the effects of dam operations, climate, and basin hydrology on Colorado River water quality.
- **RIN 8.5.1.** What elements of ROD operations (upramp, downramp, maximum and minimum flow, MLFF, high modified flow (HMF), and BHBF) are most/least critical to conserving new fine sediment inputs, and stabilizing sediment deposits above the 25,000 ft^3/s stage?

C.4. Scientific Questions that have Emerged from Past Work and That Are Addressed in This Project

During the past few years, new scientific questions have emerged with regard to water quality and to sediment transport, storage, and erosion in the Colorado River and its tributaries. Moreover, some of these questions have arisen in regard to the linkages between sediment dynamics and endangered-fish habitat, for example, habitat loss from sediment deposition in the lowermost Little Colorado River (D.M. Stone, written comm., 2013). Specific scientific questions/topics that will be addressed in the peer-reviewed scientific literature during FY2015-17 include:

- A re-evaluation of the effects of dam operations on sand transport and storage in the six mass-balance reaches of the CRe using the high-quality 15-minute measurements of sediment transport available at all mainstem gages starting in 2008.
- Has the implementation of more frequent HFEs starting in 2012 measurably influenced the dynamics of sand transport and storage in the CRe?
- Does longer-term sand storage in the CRe generally increase in the downstream direction or does the geomorphology influence sand transport such that downstream reaches (for example, the reach between RM166 and RM225) lose sand while upstream reaches gain sand?
- How does the implementation of more frequent HFEs affect water quality in the CRe on a reach-by-reach basis?
- Do tributaries other than the Paria River and Little Colorado River substantially affect the sediment budget of the CRe?
- Do long-term changes in the hydrologies of the Paria and Little Colorado Rivers exist and, if so, what are the implications of these changes for sediment management in the CRe?
- What are the linkages among hydrologic change (both natural and human-enhanced), sediment transport and dynamics, and aquatic habitat in the Little Colorado River?
- Have changes in the hydrologic and sediment-transport characteristics of the part of the Little Colorado River upstream from Blue Springs resulted in major changes to the geomorphology and aquatic habitat of the reach of the Little Colorado River downstream from Blue Springs? If so, how might continued changes affect the endangered-fish habitat in the lowermost reach of the Little Colorado River in the future?

D. Proposed Work

D.1. Project Elements

Data collection during FY15–17 will be conducted using the same methods, spatial resolution, and temporal resolution as during FY13–14. All measurements of stage, discharge, water quality, and physical measurements of suspended and bed sediment are made using standard, approved USGS techniques. The discharge, water-quality, and sediment monitoring networks on the Colorado River and its tributaries are described in Griffiths and others (2011, 2014), Topping and others (2010), Voichick and Wright (2007), Voichick (2008), and Voichick and Topping (2014). Errors in conventional suspended-sediment measurements are calculated using the methods of Topping and others (2011) and Sabol and Topping (2013). Acoustic measurements of suspended sediment are made using techniques described by Topping and others (2004, 2006a, 2007b), Wright and others (2010c), and Topping and Wright (in prep.). Proposed funding for FY15–17 positions this project to do the required work to implement the DOI-approved HFE Protocol during FY15–17.

During FY15–17, we propose to continue to serve project data and user-interactive sediment budgets through this website. In addition, work will continue to add additional data streams to this website and expand the user-interactive tools. Chief among the new tools to be developed are user-interactive duration curves. Duration curves are one of the most useful and powerful tools for conveying complicated hydrologic and water-quality datasets. We have successfully used duration curves to analyze changes in stage, discharge, and turbidity for various periods and reaches in the CRe (Topping and others, 2003; Voichick and Topping, 2014). Once the duration-curve tool is added to the website, the user will be able to plot the percentage of time any parameter served on our website is equaled or exceeded for any user-specified period.

In addition to the collection and serving of the basic stream-flow, water-quality, and sediment-transport data, time is spent in this project interpreting the data and reporting on the results and interpretations in peer-reviewed articles in the areas of hydrology, water quality, and sediment transport. The interpretive papers published by this project are designed to address key questions relevant to river management, especially to management in the GCDAMP (see proposed publication list below). The data collected in this project form the basis of the collaborations listed in the next section. All of the projects funded in the areas of physical science, biology, and socioeconomics require the data collected by this project. During FY15–17, several peer-reviewed journal articles and USGS reports will be published on the following topics:

- Analysis of Paria River and Little Colorado River hydrology 1920s-present with implications for long-term sediment management in the CRe (*lead author Topping, to be completed during FY15–16*)
- Geomorphology, hydraulic geometry, and sediment transport in the Paria River (*lead author Topping, to be completed during FY17*)
- Analysis of a decade of measurements of sediment transport in the lesser tributaries: Do the lesser tributaries matter to CRe sediment mass balance? (*lead author Griffiths, to be completed during FY15*)
- Multiple articles on the linkage among hydrology, sediment transport, and geomorphic change in the Little Colorado River, with implications for aquatic and riparian habitat in the lower Little Colorado River (*lead author Dean, to be completed during FY16–17*)
- Evaluation of effects of 2008-2016 dam operations on sediment storage dynamics within the CRe (*lead author Topping, to be completed during FY17*)

In addition to these major publications, additional data reports and interpretive reports will be published by project personnel and USGS cooperators.

D.2 Personnel and Collaborations

The USGS-GCMRC personnel on this project are: David Topping (Research Hydrologist and project chief), Ronald Griffiths (Hydrologist and deputy project chief), David Dean (Hydrologist), Nick Voichick (Hydrologist and Water Quality Specialist), Tom Sabol (Hydrologist), Joel Unema (Hydrologic Technician, part-time), Taylor Roe (Hydrologic Technician, laboratory worker), and Jason Fobair (Hydrologic Technician, student laboratory worker).

The measurements of this project are essential to the success of Project 3 (*Sandbars and Sediment Storage Dynamics*). The measurement data and the mass balance sediment budgets computed in Project 2 are compared with the morphometric sediment budgets calculated in Project 3. The major external collaborations funded through this project are with three USGS cooperators: the Arizona Water Science Center, the Utah Water Science Center, and the Center for Integrated Data Analytics. Collaborations also exist between this project and most other funded physical-sciences and biology projects of the Triennial Work Plan, mostly in a supporting role, and with researchers in academia. In previous years, academic collaborations have existed between this project and researchers at the University of Colorado, College of William and Mary, Arizona State University, Utah State University, and Northern Arizona University.

D.3 Deliverables

1. 15-minute stage, discharge, and water temperature data (updated every 1-4 hours in realtime) and other QW data from the 9 gaging stations maintained by the USGS Arizona and Utah Water Science Centers under this project are available at http://waterdata.usgs.gov/nwis and http://www.gcmrc.gov/discharge_qw_sediment/.
2. 15-minute stage, discharge, water temperature, specific-conductance, turbidity, dissolved-oxygen, and suspended-sediment-concentration and grain-size data from the stations maintained by GCMRC under this project are available at http://www.gcmrc.gov/discharge_qw_sediment/. These data are updated as frequently as every month, depending on data-collection location.
3. Mass-balance sand budgets for the CRe constructed using 15-minute sediment-transport data are served at http://www.gcmrc.gov/discharge_qw_sediment/ and updated on a monthly basis.
4. Advanced user-interactive data-analysis tools (including user-interactive duration curves) on the web at http://www.gcmrc.gov/discharge_qw_sediment/.
5. Annual water-data reports for stage, discharge, and water quality data collected by the Arizona and Utah Water Science Centers are published online.
6. At least four interpretive journal articles and top-tier USGS reports on project-relevant topics on the Colorado River and its tributaries in the CRe (see proposed publication list above).
7. At least three additional peer-reviewed data reports and interpretive reports identified during the course of this study.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

1. 15-minute stage, discharge, and water temperature data (updated every 1-4 hours in realtime) and other QW data from the 9 gaging stations maintained by the USGS Arizona and Utah Water Science Centers under this project are available at http://waterdata.usgs.gov/nwis and http://www.gcmrc.gov/discharge_qw_sediment/.
2. 15-minute stage, discharge, water temperature, specific-conductance, turbidity, dissolved-oxygen, and suspended-sediment-concentration and grain-size data from the stations maintained by GCMRC under this project are available at http://www.gcmrc.gov/discharge_qw_sediment/. These data are updated as frequently as every month, depending on data-collection location.
3. Mass-balance sand budgets for the CRe constructed using 15-minute sediment-transport data are served at http://www.gcmrc.gov/discharge_qw_sediment/ and updated on a monthly basis.
4. Annual water-data reports for stage, discharge, and water quality data collected by the Arizona and Utah Water Science Centers are published online at:
   http://wdr.water.usgs.gov/wy2012/pdfs/09380000.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09381800.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09382000.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09402000.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09402300.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09402500.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09403850.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09404115.2012.pdf
   http://wdr.water.usgs.gov/wy2012/pdfs/09404200.2012.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09380000.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09381800.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09382000.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09402000.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09402300.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09402500.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09403850.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09404115.2013.pdf
   http://wdr.water.usgs.gov/wy2013/pdfs/09404200.2013.pdf

E.2. Completed Publications

Grams, P.E., Topping, D.J., Schmidt, J.C., Hazel, J.E., Jr., and Kaplinski, M., 2013, Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design: Journal of Geophysical Research: Earth Surface, v. 118, 18p., doi:10.1002/jgrf.20050, http://onlinelibrary.wiley.com/doi/10.1002/jgrf.20050/pdf.

Griffiths, R.E., Topping D.J., Anderson R.S., Hancock, G.S., and Melis, T.S., 2014, Design of a sediment-monitoring gaging network on ephemeral tributaries of the Colorado River in Glen, Marble, and Grand Canyons, Arizona: *U.S. Geological Survey Open File Report* 2014-1137, 21 p., http://dx.doi.org/10.3133/ofr20141137.

Sabol, T.A., and Topping, D.J., 2013, Evaluation of intake efficiencies and associated sediment-concentration errors in US D-77 bag-type and US D-96-type depth-integrating suspended-sediment samplers: U.S. Geological Survey Scientific Investigations Report 2012–5208, 88 p., http://dx.doi.org/10.3133/sir20125208, http://pubs.er.usgs.gov/publication/sir20125208

Sabol, T.A., and Springer, A.E., 2013, Transient simulation of groundwater levels within a sandbar of the Colorado River, Marble Canyon, Arizona, 2004: U.S. Geological Survey Open-File Report 2013-1277, 22 p., http://dx.doi.org/10.3133/ofr20131277

Voichick, N., and Topping, D.J., 2014, Extending the turbidity record: Making additional use of continuous data from turbidity, acoustic-Doppler, and laser diffraction instruments, and suspended-sediment samples in the Colorado River in Grand Canyon: U.S. Geological Survey Scientific Investigations Report 2014-5097, 31 p., http://pubs.er.usgs.gov/publication/sir20145097

E.3. Publications in progress

Topping, D.J., and Wright, S.A., to be submitted for review during FY2014, Accurate long-term, high-resolution acoustic measurements of suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand grain size in rivers: Journal of Geophysical Research.

Topping, D.J., Wright, S.A., Griffiths, R.E., Dean, D.J., and Rubin, D.M., to be submitted for review during FY2014, Acoustic, laser-diffraction, and pump methods for measuring the concentration and grain-size distribution of suspended sediment in rivers at high temporal resolution over multi-year timescales: Theory, calibration, and error: either a U.S. Geological Survey Professional Paper or an American Geophysical Union Monograph.

E.4. Presentations at GCDAMP meetings

Episodic updates made to TWG and AMWG on the state of sediment and QW in the CRE; more frequent updates on the trigger status provided leading up to the November 2012 and 2013 HFEs.

E.5. Presentations at professional meetings

Grams, P.E., Schmidt, J.C., Topping, D.J., and Yackulic, C.B., 2012, Error and Uncertainty in High-resolution Quantitative Sediment Budgets: EOS, Transactions, American Geophysical Union.

Topping, D.J., Griffiths, R.E., Dean, D.J., Wright, S.A., Rubin, D.M., Garner, B.D., Sibley, D.M., and Reinke, T.A., 2013, Accurate sediment budgets in rivers require high-resolution discharge-independent measurements of suspended-sediment concentration: EOS, Transactions, American Geophysical Union.

Griffiths, R.E., and Topping, D.J, 2013, Measurements of sediments loads in small, ungaged, basins may be required to accurately close sediment budgets: An example from a monitoring network on the southern Colorado Plateau: EOS, Transactions, American Geophysical Union.

Grams, P.E., Buscombe, D., Hazel, J.E., Kaplinski, M.A., and Topping, D.J, 2013, Reconciliation of Flux-based and Morphologic-based Sediment Budgets: EOS, Transactions, American Geophysical Union.

Jain, S., Melis, T.S., Topping, D.J, Pulwarty, R.S., and Eischeid, J., 2013, Warm Season Storms, Floods, and Tributary Sand Inputs below Glen Canyon Dam: Investigating Salience to Adaptive Management in the Context of a 10-Year Long Controlled Flooding Experiment in Grand Canyon National Park, AZ, USA: EOS, Transactions, American Geophysical Union.

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Griffiths, R.E., Topping D.J., Anderson R.S., Hancock, G.S., and Melis, T.S., 2014, Design of a sediment-monitoring gaging network on ephemeral tributaries of the Colorado River in Glen, Marble, and Grand Canyons, Arizona: U.S. Geological Survey Open File Report 2014-1137, 21 p., http://dx.doi.org/10.3133/ofr20141137.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
X	X						2	Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem	Topping et al.	$619,000	$5,000	$50,000	$70,000	$0	$480,000	$116,300	$1,340,300
FY16																	
X	X						2	Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem	Topping et al.	$659,000	$5,000	$52,000	$72,000	$0	$496,000	$168,000	$1,452,000
FY17																	
X	X						2	Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem	Topping et al.	$671,000	$5,000	$53,000	$74,000	$0	$512,000	$219,900	$1,534,900

Project 3. Sandbars and Sediment Storage Dynamics: Long-term Monitoring and Research at the Site, Reach, and Ecosystem Scales

Initial Estimate: FY15: $1,324,600; FY16: $1,362,800; FY17: $1,439,600

GCDAMP Funding: FY15: $1,324,600; FY16: $1,267,400; FY17: $1,367,600

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B. Project Summary

This project consists of a set of integrated studies that (a) track the effects of individual High-Flow Experiments (HFEs, or “controlled floods”) on sandbars and within-channel sediment storage, (b) monitor the cumulative effect of successive HFEs and intervening operations, and (c) advance general understanding of sediment transport and eddy sandbar dynamics. While the first two efforts are focused on monitoring, the latter effort is focused on improving capacity to *predict* the effects of dam operations, because management of the Colorado River downstream from Glen Canyon Dam requires that managers balance the objective to achieve fine-sediment conservation with other management objectives. Such balancing of objectives requires comparing predicted outcomes of different dam operation scenarios, such as has been pursued in the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) process.

The effort to achieve fine-sediment conservation in the Colorado River ecosystem in Marble and Grand Canyons (CRe) is greatly constrained by the limited annual supply of fine sediments to the Colorado River from ephemeral tributaries. The challenge of rehabilitating sandbars when most of the fine-sediment once supplied to the CRe is now stored in Lake Powell reservoir has been described in many scientific articles and management documents. More than a decade of monitoring and research has demonstrated that eddy sandbars accumulate sand, as well as small amounts of clay and silt (hereafter referred to as mud), during short periods of relatively high flow, but these same sandbars typically erode during flows that occur in the months to years between the high flows requisite for sandbar building. Adoption of the HFE Protocol in 2012 established a formal procedure whereby seasonal sand and mud (together referred to as fine sediment) inflows are measured, and high flows are released from Glen Canyon Dam with the purpose of redistributing that sand and mud from the channel bed to eddies. The long-term effect of the HFE Protocol depends on the relative “gain” to eddy sandbars that occurs during the short controlled floods and the intervening “loss” that occurs during other times. The *Environmental Assessment for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam* (hereafter referred to as the HFE Protocol EA) asked, "Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?" In other words, does the volume of sand aggraded into eddies and onto sandbars during controlled floods exceed the volume eroded from sandbars during intervening dam operations?

Thus, one of the most important objectives of this project is to monitor the changes in sandbars over many years, including a period that contains several controlled floods, in order to compile the information required to answer the fundamental question of the HFE Protocol EA. The monitoring program described here continues the program implemented in the FY13–14 Biennial Work Plan and is based on annual measurements of sandbars, using conventional topographic surveys supplemented with daily measurements of sandbar change using ‘remote cameras’ that autonomously and repeatedly take photographs. Because these long-term monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, this project also includes (1) the analysis of a much larger sample of sandbars, using airborne remote-sensing data of the entire CRe collected every 4 years, and (2) periodic measurements of nearly all sandbars within individual 50 to 130 km river segments.

Another critical piece of information that will be needed to evaluate the outcome of the HFE Protocol and the LTEMP EIS will be the change in total sand storage in long river segments.

HFEs build sandbars by redistributing sand from the low-elevation portion of the channel to sandbars in eddies and on the banks. The sand available for bar building is the sand that is in storage within the channel, which is the sum of the sand contributed by the most recent tributary inputs, all the sand that has accumulated during the decades since Glen Canyon Dam was completed, and any sand that remains from the pre-dam era. The goal of the HFE protocol is to accomplish sandbar building by mobilizing only as much sand as is most recently contributed by the Paria River. Some of the mobilized sand is deposited in eddies where it maintains and builds eddy sandbars. Some of the sand is eventually transported downstream to Lake Mead reservoir. The most efficient floods for the purposes of sandbar building are those that maximize eddy sandbar aggradation yet minimize the amount of sand transported far downstream, thus minimizing losses to sand storage. Dam operations between HFEs also transport sand downstream, causing decreases in sand storage. If sand storage is maintained or increased, scientists expect the response to future HFEs to be similar to or better than that observed following recent HFEs. In contrast, depleted conditions of fine sediment in the active channel are potentially irreversible and threaten the long-term ability to rehabilitate eddy sandbars. Although the total amount of sand in the active channel is not known and may never be known, changes in the topography of the channel measured in this project reveal where fine sediment accumulates, where it becomes depleted, and whether or not older fine sediment deposits are being progressively eroded by HFEs and other parts of the flow regime.

This project also includes five research and development components: (1) improving methods for making sandbar surveys rapidly and at low cost; (2) investigating bedload sand transport; (3) developing a method to estimate the thickness of submerged sand deposits, (4) developing a method to map submerged aquatic vegetation, and (5) developing of a new large-scale sandbar deposition/erosion model. These projects are, respectively, designed to improve monitoring methods, improve estimates of sand transport, develop a new tool to estimate total sand storage, develop a new tool to map submerged aquatic vegetation and improve acoustic bed sediment classifications, and develop new tools for predicting how management actions including HFEs and daily dam operations affect resources.

C. Background

The many sediment-related goals and objectives of the Glen Canyon Dam Adaptive Management Program (GCDAMP) can be distilled into one question: "What actions will create and maintain the largest and most widely distributed fine-sediment deposits throughout the Colorado River ecosystem (CRe) in the context of a limited fine-sediment supply." Currently, all "actions" are associated with dam operations, but future actions might include riparian vegetation management (see Project Element 11.5). Other potential actions include augmentation of the fine sediment supply, but the construction of sediment augmentation facilities is not currently under consideration.

The effort to build fine-sediment deposits in the CRe is greatly constrained by the limited annual supply of fine sediment provided by the Paria River and other tributaries. The CRe was perturbed into a condition of fine sediment deficit following construction of Glen Canyon Dam, wherein the capacity of the Colorado River to transport fine sediment often exceeds the annual resupply rate. During the first 30 years after dam construction, a large amount of fine sediment was evacuated from the CRe (Topping and others, 2000; Grams and others, 2007). The evacuation of fine sediment from Glen, Marble, and eastern Grand Canyons resulted in a decline in the number and size of sandbars in the eastern half of Grand Canyon National Park (Schmidt and others, 2004; Wright and others, 2005).

Achieving widespread and abundant distribution of eddy sandbars is desirable, because there are many linkages between the distribution and amount of fine sediment in the CRe and several ecosystem and management goals. Sandbars are used as camping beaches, form a major component of aquatic habitats, and are a source of aeolian sand for the upland ecosystem. Management and ecosystem goals include: maintenance of sandbars used by boaters and hikers, creation of sandbar-associated backwater habitats used by native fish, and maintenance of exposed bare sandbars that are available for redistribution by wind to upslope areas.

Monitoring and research also focuses on the distribution of fine sediment elsewhere in the CRe. Recent research demonstrates that the distribution, abundance, and size of fine sediment on the bed of the active channel control the transport of fine sediment during HFEs. In turn, higher suspended sediment concentration during HFEs enhances the rate at which eddy sandbars are constructed during those controlled floods. Additionally, the distribution of fine sediment on the channel bed affects primary production and aquatic habitats. We use the term "sediment" to refer to alluvium of all sizes, "fine sediment" to refer to sand, silt, and clay (all sediment < 2 mm), and "sand" to refer to sand-sized sediment only (0.0625 – 2 mm). The focus of this project is on the sand-size component of fine sediment, because most fine sediment resources in the CRe are primarily composed of sand.

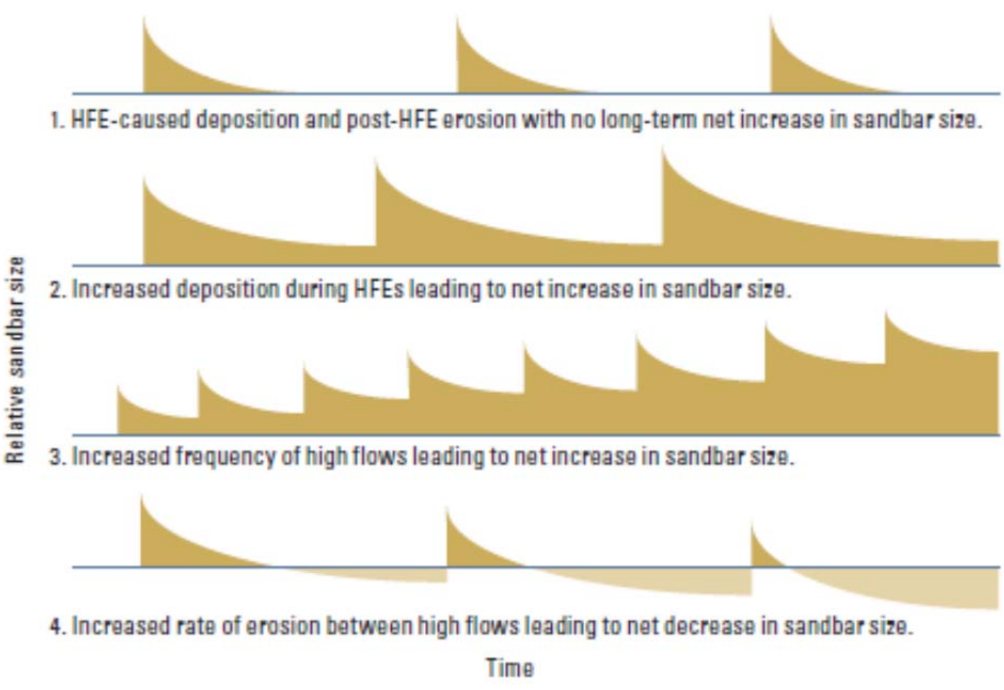

Figure 1. Conceptual diagram illustrating possible trajectories of sandbar size in relation to the frequency of High Flow Experiments (HFEs), the amount of deposition caused by HFEs, and the amount of erosion that occurs between HFEs (figured adapted from Schmidt and Grams, 2011). The case shown in 1 shows a hypothetical situation where the amount of HFE deposition equals the amount of intervening erosion. Cases two and three are hypothetical situations where the total amount of HFE-induced deposition, which is the magnitude of HFE deposition multiplied by the frequency of HFEs, exceeds the magnitude of intervening erosion. In case 4, the hypothetical rate of erosion that occurs between HFEs exceeds the magnitude of HFE-induced deposition. The purpose of the monitoring activities described in Project 3 is to determine which of these hypothetical cases occurs during the period of implementation of the HFE Protocol.

More than a decade of monitoring and research demonstrates that eddy sandbars are dynamic topographic features that accumulate sand during short duration high flows when fine sediment previously supplied by tributaries is redistributed from the deepest parts of the channel to higher elevations in eddies and along the channel margins. These same sandbars and channel-margin deposits typically erode during periods of normal power-plant operations, especially during months when there is no inflow from tributaries (Schmidt and others, 1999; Hazel and others, 1999; Topping and others, 2006; Hazel and others, 2010; Schmidt and Grams, 2011). The HFE Protocol established a formal procedure whereby seasonal inflows of sand are measured by Project 2, and high flows are released from Glen Canyon Dam with the purpose of redistributing that sand from the channel bed to eddies. The long-term effect of the HFE Protocol depends on the relative “gain” to eddy sandbars that occurs during short controlled floods and the intervening “loss” that occurs during other times.

Previous monitoring activities associated with Projects 2 and 3 have demonstrated that, in some multi-year periods, fine-sediment is supplied to the CRe by the Paria River and other tributaries at a higher rate than the rate of export downstream to Lake Mead reservoir. This positive fine sediment mass balance typically occurs when there are many floods on tributary streams and relatively small total annual releases of water from Lake Powell (Grams and others, 2013). In contrast, more fine sediment is evacuated from the CRe in those multi-year periods when there are only small floods in tributaries and there are large releases from Lake Powell. Monitoring in the CRe has not occurred for a sufficiently long period to determine if a decadal-scale quasi-equilibrium in the amount of fine sediment in the CRe is achievable, nor if the HFE Protocol can significantly improve the chances for achievement of quasi-equilibrium (Fig. 1). The monitoring activities described here provide the fundamental evidence on which evaluation of the long-term fate of fine sediment deposits will be made.

C.1. Scientific Background

Completion of Glen Canyon Dam caused a 90-percent reduction in fine-sediment supply to the Colorado River in Marble and Grand Canyons (Topping and others, 2000), because all fine sediment produced in the upstream watershed is trapped in Lake Powell. Operations of Glen Canyon Dam, which control the rate of release of reservoir waters into the CRe, create a flow regime that is dramatically different from that produced by the annual melting of the Rocky Mountain snowpack and the late summer/early fall North American monsoon and thunderstorm season (Topping and others, 2002). These changes to the flow regime and sediment supply caused deep scour and armoring of the river bed between the dam and Lees Ferry, 25 km downstream from the dam (Pemberton, 1976; Williams and Wolman, 1984; Grams and others, 2007). Scour was widespread in this segment, because the sand and fine gravel in the channel was easily eroded (Grams and others, 2007). Downstream from Lees Ferry in Marble and Grand Canyons, inputs of large cobbles and boulders from tributaries create rapids and change the nature of the river and the style of response to sediment deficit. The boulder deposits that form rapids have not been eroded and in some cases have aggraded (Magirl and others, 2005). In contrast, areas of the bed covered by fine sediment have been eroded. Thus, the water surface profile of the Colorado River in Marble and Grand Canyons has not significantly changed except at some rapids (Magirl and others, 2005), but a large amount of sand has been eroded from deep pools, and many eddy sandbars are much smaller than they once were (Schmidt and others, 2004). Because systematic measurements of fine-sediment thickness have never been made, the total volume of fine sediment present (or eroded) is not known.

Many studies conducted since the 1970s have shown that (1) post-dam controlled floods cause increases in sandbar size throughout the CRe (Hazel and others, 2010; Schmidt and Grams, 2011); (2) normal dam operations (i.e., hydro-peaking) cause sandbar erosion whose rates are greatest immediately following floods (Grams and others, 2010; Schmidt and Grams, 2011); and, (3) there is a large variability in the magnitude of sandbar response from place to place (Hazel and others, 1999, 2010; Schmidt and others, 1999). Topping and others (2000) showed that the supply of sand available to build sandbars is limited, and Schmidt (1999) showed that controlled floods that build some sandbars sometimes do so at the expense of erosion of sand from other, upstream eddy sandbars.

The Role of Sediment Budgets in Fine Sediment Monitoring

Sandbars are one component of the total sediment budget for the Colorado River. The sediment budget, or sediment mass balance, is simply the accounting by mass (or volume) of all sediment entering and exiting any segment of a river. This budget may be expressed as:

$$I - O = \Delta S, \tag{1}$$

where I is the sum of all inputs, O is the sum of all outputs, and ΔS is the net change in the sediment deposits that occurs within that segment of river. When inputs exceed outputs, sediment accumulation occurs; when outputs exceed inputs, sediment evacuation occurs. To provide greater spatial resolution, equation (1) can be partitioned by the elevation zone in which ΔS occurs. Sand stored low in the active channel (ΔS_{low}) is always underwater and sand stored higher in the active channel (ΔS_{high}) is only be occasionally inundated. Thus,

$$\Delta S = \Delta S_{low} + \Delta S_{high}. \tag{2}$$

These two storage components can be further subdivided based on other criteria such as whether the sediment deposits occur within eddies or in the main channel.

We use “low” to refer to fine-sediment deposits below the stage associated with the 8,000 ft^3/s discharge and “high” to refer to fine-sediment deposits above the 8,000 ft^3/s stage. The low-elevation deposits are always underwater except during the trough of some flow fluctuations; these deposits consist of the lower parts of eddy sandbars and patches of sand on the river bed. These low-elevation deposits are relevant to aquatic habitat and, in the case of sandbars in eddies, they underlie the sediment that occurs at higher elevation. The high-elevation fine-sediment deposits are alternately inundated and exposed, depending on the flow regime. These deposits are the high-elevation parts of sandbars and are used as camping beaches, support riparian vegetation, and support other upland resources. High-elevation deposits include both those deposits that are inundated by normal dam operations and controlled floods and those deposits that are no longer inundated. This project is concerned primarily with deposits at and below the elevation inundated by controlled floods. The higher-elevation pre-dam deposits are the focus of Project 4.

Low- and high-elevation deposits are coupled through processes of erosion and deposition by streamflow, erosion and deposition by wind, and mass failure. This coupling means that changes in ΔS will affect both low- and high-elevation sediment. Therefore, predictions about the long-term fate of sandbars must be based on understanding and, by extension, the ability to predict, the long-term trend in ΔS. For these reasons, all sandbar research and monitoring is designed around this concept of the sediment budget.

Measurements of suspended sediment were initiated in 1999 to measure sediment inputs and outputs for each segment of the Colorado River between the measurement stations; thus, each segment of the Colorado River is a sediment budgeting reach[1] (Fig. 2). The measurements of inputs and outputs (I and O in equation 1) made in Project 2 can be used to calculate ΔS, and this approach tracks the large-scale accumulation and downstream redistribution of tributary inputs that is essential for implementation of the HFE Protocol. However, this calculation of ΔS derived from gaging stations measurements and equation (1) does not distinguish between the changes that occur in ΔS_{low} or in ΔS_{high}; thus, the calculation of ΔS does not reveal whether equation (1) is of immediate significance to increasing sandbar size, campsite area, increasing the area of sand available for plant colonization, or other topographic changes of recreational or ecological significance. Additionally, this calculation of ΔS does not reveal whether topographic changes in sand deposits were associated with changes in bed-sediment grain size, which is important for assessing the mobility of the sand during future HFEs. Further, calculation of equation (1) does not reveal changes at specific local locations.

In response to the need to provide spatially explicit measurements that would demonstrate the implications of calculations based on equation (1), direct measurements of ΔS based on repeated topographic measurements in short (2- to 5-km long) reaches were made between 2000 and 2004. Measurements of channel bed bathymetry were made using sonar and the topography of exposed deposits was measured using airborne LiDAR, aerial photogrammetry, and conventional topographic surveys (Hazel and others, 2008; Kaplinski and others, 2009, 2014). Repeat measurements at different times were made at seven reaches between River Mile (RM) 0 and RM 87 (Fig. 2). This monitoring program was a substantial advancement beyond earlier monitoring programs, because nearly all of the channel was mapped, in contrast to previous efforts that made measurements at widely-spaced cross-sections or isolated sandbars.

[1] In this proposal, we refer to observations and study areas that span a variety of spatial scales. We use "monitoring site" to refer to monitoring locations that are at the scale of individual sandbars, 100's of meters in length. We use "short reach" to refer to study reaches that include many sites and are on the order of 2 to 5 km in length. We use "long reach" or "sediment budgeting reach" to refer to segments of the river that encompass the entire channel between fine-sediment monitoring gages; these reaches are 50 to 130 km in length.

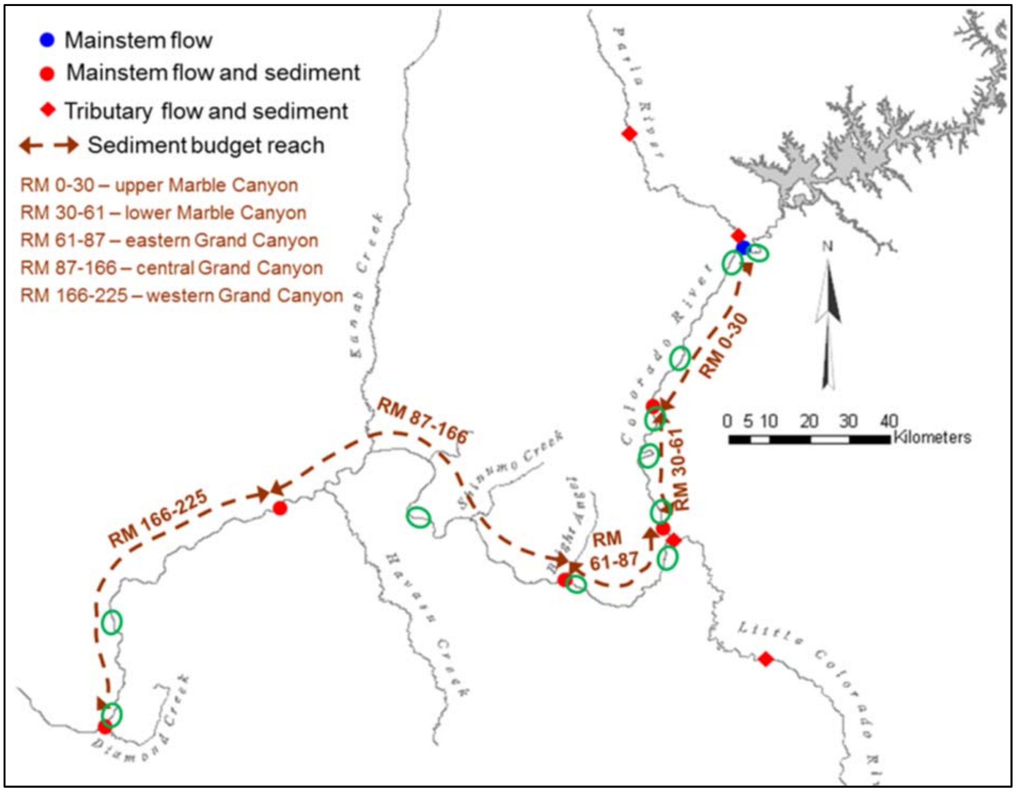

Figure 2. Map showing the Colorado River between Glen Canyon Dam and Diamond Creek. The stations for suspended sediment transport monitoring (Project 2: Streamflow, Sediment Transport, and Water Quality) are shown by the red circles. The short reaches where sediment storage was mapped between 2000 and 2004 are shown by the green ovals. Based on analysis of these data, the current sediment storage monitoring plan calls for mapping 50 to 80 percent of the channel in the segments between the sediment monitoring stations. In 2009 and 2012, most of the long sediment budgeting reach between RM 30 and RM 61 was mapped. In 2011 and 2014, most of the sediment budgeting reach between RM 61 and RM 87 was mapped. In 2013, most of the sediment budgeting reach between RM 0 and RM 30 was mapped.

Results from this monitoring program demonstrated that 90 percent or more of the temporary fine sediment accumulation in the modern river occurs in the low-elevation parts of the active channel (Hazel and others, 2006). Ironically, the deposits that are generally of greatest management interest (high-elevation sandbars) comprise only about 10 percent of the fine sediment in the system. Perhaps the most challenging finding related to development of a robust fine sediment monitoring program was that ΔS computed for each of the study reaches based on repeated measurements of topography yielded different values than ΔS computed using equation (1) using the difference between fine sediment inflows measured at gaging stations (Topping and others, 2006; Grams and others, 2011, 2013). Although the study reaches were much shorter than the sediment budgeting reaches, Hazel and others (2006) and Grams and others (2011, 2013) expected that simple extrapolation of the computed ΔS term for the measurement reaches would approximate the ΔS term computed for the longer sediment budgeting reaches. However, this was not the case, and extrapolation of ΔS measured in the short reaches yielded a very different value of ΔS from that computed using equation (1) and the gaging station data collected in Project 2.

Temporal and Spatial Variability of Fine-Sediment Deposits and Implications to Monitoring

Grams and others (2011, 2013) found that this discrepancy stems from the inability to correctly extrapolate measurements from the short reaches to larger spatial scales. Extrapolation failed for two major reasons: changes in bed topography are (1) highly localized and (2) spatially variable. Schmidt and others (2004) had earlier demonstrated a high degree of spatial variability in the behavior of sand deposits caused by the 1996 controlled flood. They showed that large changes in sediment storage had been concentrated in eddies and in pools in the channel units adjacent to eddies. Similar and nearby eddy sandbars did not necessarily change in the same ways—scour in one eddy was sometimes offset by an equal or larger magnitude of deposition in the next eddy. Grams and others (2011, 2013) also found that the magnitude of change in bed topography in some channel pools can be very large. Thus, Grams and others (2011, 2013) determined that the net ΔS of a long sediment budgeting reach is the sum of many local ΔS terms in individual channel units; ΔS in some of these units is positive, but ΔS is negative elsewhere. In many cases, ΔS is larger at a local scale than at larger scales, and ΔS at a large scale is the net difference among very large values that occur in relatively short parts of the channel.

These findings make clear why it is nearly impossible to extrapolate the calculations of ΔS measured in short study reaches to longer sediment budgeting reaches. Without better knowledge of the spatial distribution and size of each channel unit where large changes in fine sediment storage can occur, and without knowing the physical reasons that determine the inherent variability in response to varying flows, it is not possible to extrapolate measurements from the short reaches to longer reaches (Grams and others, 2013). These findings demonstrate that in order to determine whether sediment storage in each storage environment – at low and high elevations and in the channel and eddy storage environments – is increasing, decreasing, or stable, requires repeat measurements of sand storage throughout the long sediment budgeting reaches. The proposed fine-sediment monitoring includes measurements of channel and eddy sand storage at the scale of the long sediment budgeting reaches.

In response to these findings, a long-reach monitoring program (also known as the "channel mapping" project) was initiated in 2009 when lower Marble Canyon was mapped. Mapping of eastern Grand Canyon followed in 2011, and a repeat map of lower Marble Canyon was measured in 2012. The first mapping of upper Marble Canyon occurred in 2013, and a repeat map of eastern Grand Canyon was made in 2014 (Fig. 2). The river bed is mapped with multi-beam and single-beam sonar, the topography of exposed sand deposits is mapped with conventional survey equipment, and bed-sand grain size is also measured. These data are combined and the final product for each sediment budget reach is a high-resolution (1-m^2 grid size) digital elevation model (DEM) of the mapped segment.

Preliminary results from the repeat mapping of lower Marble Canyon in 2012 depict changes in sediment storage throughout this 50-km river segment. During the period between the initial and the repeat measurement(2009 – 2012), the sediment budget calculated from measurements of suspended sand transport (Project 2) made at gages at RM30 and RM 60 was significantly negative (Fig. 3). The repeat measurements of the channel bathymetry and topography also indicated net erosion during the same period, and these measurements showed where the ΔS actually occurred. Although the absolute value of the ΔS term calculated from equation (1) was greater that the value calculated from the repeated mapping of the channel, but the agreement in large-scale ΔS calculated by the two methods is well within the respective ranges of uncertainty (Fig. 3). Because both calculation methods have large uncertainty, the comparison shown in Figure 3 provides a valuable verification of both measurement techniques. For this 3-year time period, both methods have similar uncertainty. While the uncertainty associated with the budget computed from measurements of sand transport increases with the length of time over which the

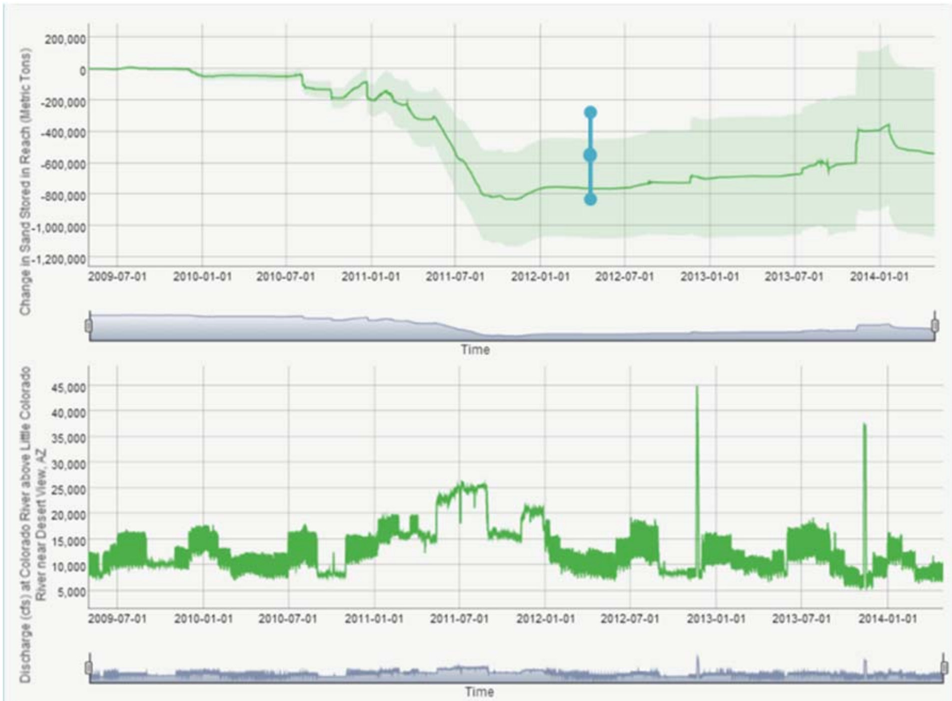

Figure 3. Sand budget for May 1, 2009 to April 30, 2014 for lower Marble Canyon (upper plot) and discharge of the Colorado River at the downstream end of the segment for the same period (lower plot). The sand budget computed by the difference in sand transport at the upstream and downstream ends of the reach is shown by the solid line with the shaded region indicating the uncertainty. Each point on the line is the sand budget for the time period between the start date and the date indicated on the horizontal axis. The uncertainty associated with each measurement contributes to the total uncertainty and increases quasi-linearly with time. The morphologic sand budget for the same reach computed by the measurements of deposits in the channel in 2009 and 2012 is shown by the filled circle with error bars, shown at the time at which the repeat measurements were made (May 2012).

computations are made (Fig. 3), the uncertainty associated with the budget calculated from the repeat channel mapping would be approximately the same for any time period. Thus if one is interested in the net change in sediment storage for a ~20-year interval, the uncertainty associated with the budget computed from measurements of transport may span more than 4 million metric tons (~8 years of Paria sand inputs), while the uncertainty associated with repeat topographic measurements will still be about 600,000 metric tons (~1 year of Paria River sand inputs). The budget computed from measurements of sediment flux provides the measurements of short-term sediment accumulation necessary to implement the HFE protocol. However, over the period of long-term management actions, only the repeat measurements of the channel will provide estimates of significant storage change (i.e. with an uncertainty that is less than the estimate of the magnitude of storage change).

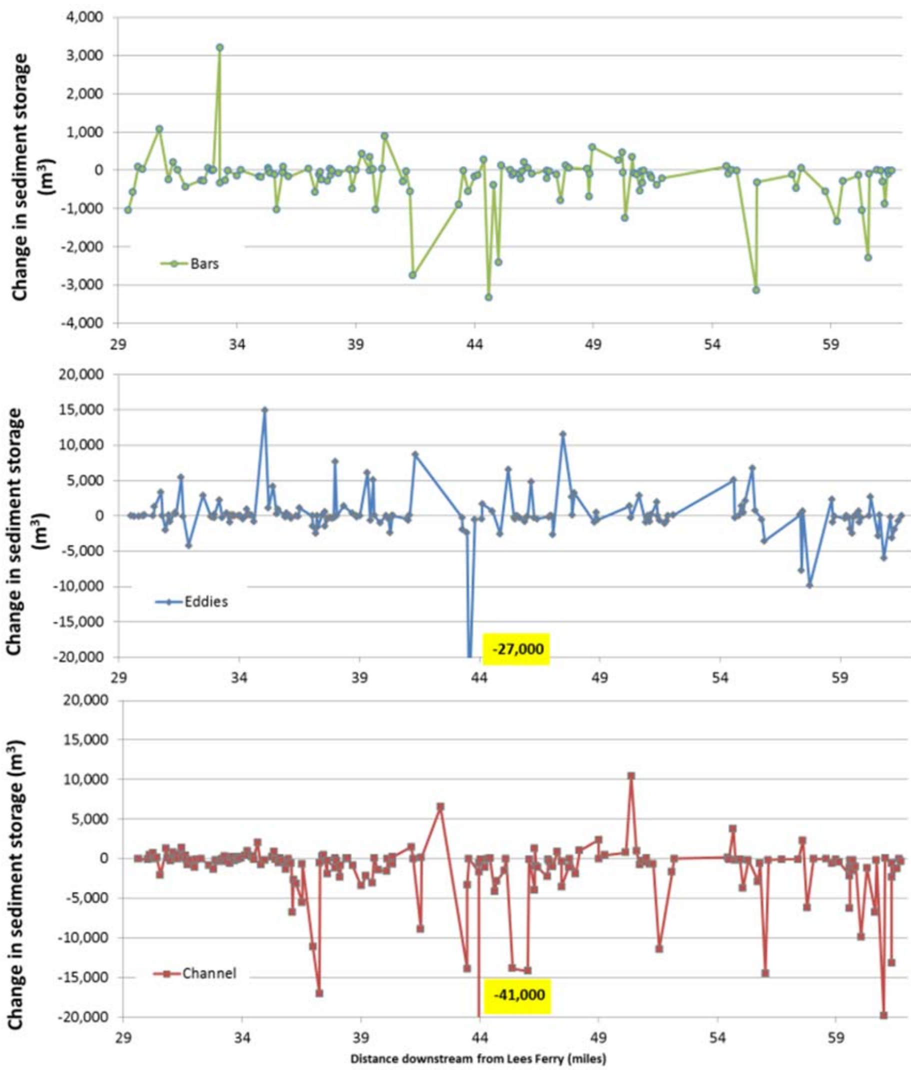

Figure 4. Change in sediment storage between May 2009 and May 2012 for lower Marble Canyon computed by comparing the maps (DEMs) of the channel made in those two years. Each marker represents a surveyed pool. Note the different vertical scales. In this period with a net decrease in sediment storage (Fig. 4), the eddies exhibited a small net increase in storage while the bars and the channel both lost sediment. The largest changes occurred in the channel and were concentrated in relatively few pools.

Grams and others (2011, 2013) illustrated the interpretive power of increased spatial resolution in depicting ΔS that is derived from the channel mapping data (Fig. 4). During the period between May 2009 and May 2012, there was net erosion of the high elevation parts of eddy sandbars (ΔS_{high}). At lower elevation (ΔS_{low}), erosion of fine sediment deposits in the channel occurred but deposition occurred in eddies. Thus, even though the entire sediment budget reach of lower Marble Canyon evacuated fine sediment, the eddies were efficient traps for some of the fine sediment being transported downstream. If it were not for this deposition of fine sediment at low elevation in some eddies, a larger amount of fine sediment would have been evacuated from lower Marble Canyon during this period.

Long-Term Change in Eddy Sandbars and Campsites

Sandbar monitoring in the FY13–14 work plan included annual monitoring of long-term monitoring sites and evaluation of sandbars throughout the CRe from remote sensing. Results from the annual sandbar monitoring (Project Element 3.1.1) show that while sandbars at the long-term monitoring sites were relatively small before the November 2012 HFE, sandbars at these sites were relatively large in October 2013, 10 months following the 2012 HFE (Fig. 5). Analysis of images collected from remote cameras at the same long-term monitoring sites show that the November 2013 HFE also resulted in net sandbar deposition. These data indicate that HFEs have resulted in net increases in sandbar size in Grand Canyon (downstream from river mile 62) since the period of initial monitoring in the early 1990s. In Marble Canyon, HFEs cause relatively short-term increases in sandbar size, and sandbars remain similar in size or smaller than in the early 1990s.

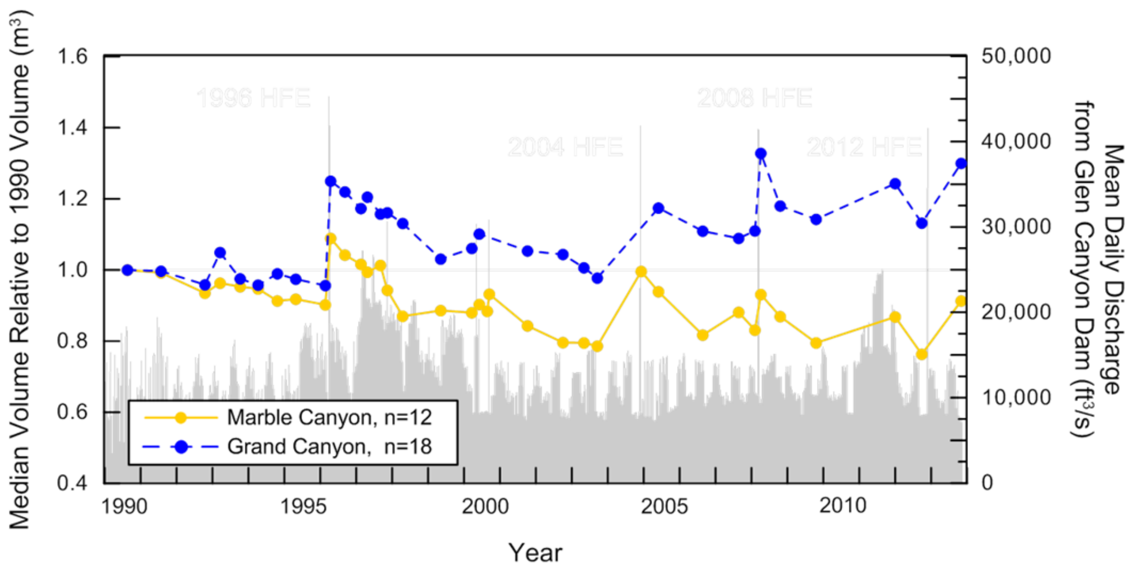

Figure 5. Sandbar size from 1990 to October 2013 (preliminary data provided by Joseph E. Hazel, Jr.).

Evaluation of the aerial photographs (Ross and Grams, in preparation) provides a somewhat longer-term perspective (going back to 1984) on the effect of HFEs on sandbars in Marble Canyon (Project Element 3.1.2). These results show that the area of sandbars exposed above the 8,000 ft^3/s stage in Marble Canyon was generally larger during the era of post-dam controlled floods (April 1996, May 2002, May 2005, and May 2009) compared with the post-dam period before controlled floods (June 1990 and March 1996). Hazel and others (in preparation) are developing a more detailed comparison of sandbar sizes following recent HFEs to those following the 1983 and 1984 floods (see Project 3.1.4 for summary of these results).

One of the FY13–14 research projects involved the investigation of the relation between changes in campsite area and causal mechanisms. Preliminary results from this project indicate that while vegetation expansion can be a significant cause of campsite area change at some sites, sandbar erosion and deposition cause the majority of increases and decreases in campsite area since 1998 (Hadley and Grams, in preparation). This effort also included an assessment of uncertainty in the campsite monitoring methods that will be incorporated in future reports on campsite area.

Canyon-Wide Remote Sensing of Sandbars and River Geomorphology

Remote sensing images from overflights are used to map the area of sand above the 8,000 ft^3/s stage. The maps provide a synoptic assessment of high elevation sand area. Maps of sand area from 2002 and 2009 overflights will be completed by the end of 2014. Data from the 2005 overflight are not being used to synoptically map sand area for the entire river corridor, because they have a large degree of spectral variability. The 2005 data have been used to map area of high elevation sand and other resources including riparian vegetation for shorter segments of the river (Ross and Grams, in prep.; Sankey and others, in review). Data from the most recent overflight in 2013 will be used to map high elevation sand area in this workplan.

Sand area is mapped for 1300 large eddies along the river. These eddies are generically delineated to include the majority of sandbars and sandy shorelines on the river. However, these eddies include finer scale geomorphic variability that has not been exhaustively delineated. In order to better understand variability in the distribution of high elevation sand area, there is an immediate need for a geomorphic base map to segregate the synoptic maps of high elevation sand area by geomorphic setting. Previous studies have completed detailed geomorphic basemaps for short segments (e.g. Hereford, 1996; Hereford and others, 2000; Schmidt and others, 2004) or system-wide inventories of specific resources, such as eddies that contain backwaters (Grams and others, 2010). A geomorphic basemap will be completed in this workplan for the entire river, which will build on the previous mapping of shorter segments or specific resources. The map will have a relatively few, simple map units of: eddies; sand deposits within eddies; sand deposits along channel margins (not within eddies); debris fans; gravel bars; talus; and bedrock, that will enable variability of high elevation sand area to be examined by geomorphic setting. The basemap will similarly be useful for mapping of other resources, in particular riparian vegetation and aeolian sand, conducted in projects 11 and 4, respectively.

Progress on Development of Numerical Models to predict Small-Scale and Large-Scale Changes in Fine-Sediment Storage

Better understanding of the physical controls on eddy dynamics will contribute to improved predictive capability through modeling. Documented and well-verified models have been produced to predict main-stem stream flow throughout Marble and Grand Canyons (Randle and Pemberton, 1987; Wiele and Smith, 1996; Wiele and Griffin, 1997; Magirl and others, 2008) and sediment flux at approximately 50-km segments between RM 0 and RM 87 (Wright and others, 2010). These models can be used to predict sediment availability for planning reservoir releases (Wright and Grams, 2010) but do not easily facilitate prediction of sandbar response. Wiele and others (2007) coupled the canyon-scale models with detailed eddy models in order to provide better predictions of bar building and erosion. This approach assumed all eddies behaved similarly, with the magnitude of erosion and deposition scaled by eddy size. We now know that these assumptions are too simplistic and that a predictive canyon-scale model for eddy response will have to incorporate the observed site-to-site variability in erosion and deposition. In the FY13–14 work plan, progress was made in identifying the sources of eddy sandbar variability (Grams and others, 2013) and towards developing a model that will be used, in the current work plan (see Project Element 3.3), to investigate the effects of channel geometry on flow and patterns of deposition and erosion in eddies (Alvarez and others, 2013; Alvarez and others, in preparation). This systematic investigation into the causes of eddy sandbar variability using a mechanistic model will facilitate development of an operational model for predicting sandbar response to flow and sediment supply (Project Element 3.3).

Understanding the Significance of Bedload Transport

One uncertainty in estimates of sand flux (Project 2) and computation of sand budgets over long reaches that is not attributable to instrument error and which can be addressed through experimental design is the contribution of bedload sand flux to the total transport. Present acoustic sediment monitoring captures the suspended sand flux but not the flux of sand which moves as bedload. Instead, bedload sand flux is estimated using a constant proportionality with suspended sand flux at each gaging station (Topping and others, 2010). The purpose of Project 3.4 is to better incorporate bedload flux into total sand flux estimates, in order to reduce the uncertainty in estimates of total sand flux and, by extension, sand mass balance. This will be achieved by measuring bedload flux and developing parameterizations for bedload flux based on routinely measured quantities such as discharge and suspended sediment load.

C.2. Management Background

The various goals, strategic science questions, information needs, and desired future conditions that have been developed by stakeholders of the GCDAMP can be distilled into one overarching question: "What actions will create and maintain the largest and most widely distributed fine-sediment deposits throughout the Colorado River ecosystem (CRe)."

Sediment-related goals were most recently articulated in the August 2011 statement of Desired Future Conditions developed by Adaptive Management Work Group. In this document, the goals related to fine-sediment resources are to "maintain adequate sand bars (including camping beaches) for recreation in Glen Canyon National Recreation Area and Grand Canyon National Park and enhance as needed once maintained" and "maintain nearshore habitats for native fish and enhance as needed once maintained."

Further guidance on monitoring needs is provided by the HFE Protocol EA. The central sandbar-related question identified in the HFE Protocol EA is, "*Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?*" The science plan for the EA includes the following specific science questions related to sandbars and camping beaches: (1) Will multiple high flows conducted over a period of 10 years result in net increases in sandbar area and volume?; (2) With the available sand supply (i.e. tributary inputs), is the approach of using repeated floods to build sandbars sustainable?; and, (3) Will multiple high flows conducted over a period of 10 years result in net increases in campsite area along the Colorado River? This Project 3 work plan includes monitoring to address each of these questions.

Previous statements of GCDAMP goals addressed in this project include the following:

- Goal 8: Maintain or attain levels of sediment storage within the main channel and along shorelines to achieve GCDAMP ecosystem goals.
- Goal 9: Maintain or improve the quality of recreational experiences for users of the Colorado River ecosystem within the framework of GCDAMP ecosystem goals. *The monitoring provides information on the size and abundance of sandbars, which are resources that affect the recreational experiences of Colorado River users.*
- Goal 11: Preserve, protect, manage, and treat cultural resources for the inspiration and benefit of past, present, and future generations. *The project includes monitoring sandbars that provide a source of sediment, through aeolian transport, to high-elevation sand deposits that contain archaeological resources.*

Because sediment monitoring addresses the physical framework of the ecosystem, which underlies many biological resource objectives, Project 3 also indirectly supports achievement of the following GCDAMP goals:

- Goal 1: Protect or improve the aquatic food base so that it will support viable populations of desired species at higher trophic levels. *The proposed monitoring supports this goal by providing information on the size and distribution of channel substrate.*
- Goal 2: Maintain or attain a viable population of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats. *The proposed sandbar and sediment storage monitoring supports this goal by providing information on sandbars which create backwaters, a habitat used by native fish.*
- Goal 6: Protect or improve the biotic riparian and spring communities within the Colorado River ecosystem, including threatened and endangered species and their critical habitat. *The sediment storage and sandbar monitoring tracks the status of the fine-sediment deposits which provides the substrate for riparian vegetation and marsh communities.*

The 2003 GCDAMP Strategic Plan identified Core Monitoring Information Needs (CMINs) related to sediment storage (goal 8). The CMINS that are addressed in Project 3 are listed below. For each, the prioritization ranking applied by the GCDAMP Science Planning Group (SPG) in 2006 is also included. In addition, several Strategic Science Questions (SSQs) were identified by scientists and managers during the knowledge assessment workshop conducted in the summer of 2005 (Melis and others, 2006).

- **CMIN 8.1.1.** Determine and track the biennial sandbar area and fine-sediment volume and grain-size changes within eddies below 5,000 cfs stage, by reach. (fourth-ranked goal 8 CMIN). ***Addressed in project 3.2.***
- **CMIN 8.2.1.** Track, as appropriate, the biennial or annual sandbar area, volume, and grain-size changes within and outside of eddies between 5,000 and 25,000 cfs stage, by reach. (second-ranked goal 8 CMIN). ***Addressed in projects 3.1.1, 3.1.2, and 3.2.***
- **CMIN 8.5.1.** Track, as appropriate, the biennial sandbar area, volume, and grain-size changes above 25,000 cfs stage, by reach (fifth-ranked goal 8 CMIN). ***Addressed in projects 3.1.1, 3.1.2, and 3.2.***
- **CMIN 8.6.1.** Track, as appropriate, changes in coarse sediment (> 2 mm) abundance and distribution (unranked goal 8 CMIN). ***Addressed in project 3.1.2 and 3.2.1.***
- **CMIN 9.3.1.** Determine and track the size, quality, and distribution of camping beaches by reach and stage level in Glen and Grand Canyons (top-ranked goal 9 CMIN). ***Addressed in project 3.1.1.***
- **SSQ 4-1.** Is there a “Flow Only” operation (that is, a strategy for dam releases, including managing tributary inputs with BHBFs, without sediment augmentation) that will rebuild and maintain sandbar habitats over decadal time scales? ***Addressed in all project components.***
- **SSQ RIN 5:** What is the rate of change in eddy storage (erosion) during time intervals between BHBFs? ***Addressed in project 3.2.***

C.3. Key Monitoring and Research Questions Addressed in this project

The goals, science questions, and information needs listed above are often overlapping and have various degrees of specificity. We have, therefore, translated them into the following set of monitoring and research questions addressed in Project 3:

1. What is the long-term effect of dam operations, including controlled floods, on the distribution, abundance, and size of eddy sandbars above the 8,000 ft^3/s stage and on total amount of fine sediment stored in the active channel at low and high elevation? How do these changes affect recreation and ecosystem resources such as camping beaches, substrate for riparian vegetation, in-channel backwater habitat, and areas of bare sand that are redistributed by wind to upslope locations? ***Addressed in Project Elements 3.1.1, 3.1.2, and 3.2.***
2. Do individual HFEs continue to build sandbars with the same effectiveness observed in response to previous HFEs (i.e. do floods of similar magnitude build a similar number of sandbars of similar size?)? Do individual sandbars respond significantly differently to different HFEs? How does sandbar size and shape prior to HFEs affect the bar-building response? ***Addressed in Project Elements 3.1.1 and 3.1.3.***
3. What are the causes of variability in sandbar response to floods and intervening dam operations? Can we categorize this variability and incorporate this in a model for sandbar response? This builds on sandbar monitoring (Question 1) to support prediction of sandbar response. ***Addressed in Project Element 3.3, using data from elements 3.1.1, 3.1.3, and 3.1.4.***
4. What is the long-term net effect of dam operations, including high flows, on changes in low-elevation sand storage (the sand below the 8,000 ft^3/s stage) and bed-sediment grain size? These changes are relevant to backwaters and other aquatic habitat, the foundation of eddy sandbars, and the relative partitioning of transported sediment into eddies and downstream, which ultimately determines whether the use of experimental high flows is sustainable. ***Addressed in Project Element 3.2.***
5. What is the relative abundance and spatial distribution of fine and coarse bed sediments and submerged aquatic vegetation, and how do these affect primary production, fish habitat, and modeled sediment fluxes? This builds on low elevation sand monitoring (Question 5) to support sediment transport and biological prediction. ***Addressed in Project Element 3.2.***
6. Can we improve reach-scale estimates of sand flux and sediment mass balance by better quantifying the contribution of bedload transport? Can we use the geometry and sedimentology of bedforms as an indicator of 'bed state;' i.e. sand-enriched or sand-depleted bed conditions. ***Addressed in Project Element 3.4.***

D. Proposed Work

This project is divided into four monitoring and research elements and one support element. The first two project elements (3.1 and 3.2) are monitoring projects, each with minor research aspects to improve monitoring methods and protocols. Two other elements (3.3 and 3.4) are research projects that contribute to improving the monitoring program and improving predictive capacity in analyzing future dam operations and tributary fine-sediment supply rates. The control network and survey project element (3.5) advances our capacity for making repeatable geospatial measurements and supports all other Project 3 elements, as well as other GCMRC projects.

D.1 Outline of Monitoring Strategy

Monitoring programs must address trade-offs between measurement precision, spatial coverage of measurements, measurement frequency, and cost. It is generally not possible to monitor a large number of sites, frequently and at high precision, without extremely high cost. These issues are addressed in this project with a tiered monitoring strategy that consists of multiple interconnected project elements. In section C.1, above, we described the concept of the sediment budget and many of the challenges associated with monitoring sediment storage in the CRe that contribute to the need for large (spatially extensive) sample sizes. We distinguished between sediment storage monitoring that is concerned with measurement of ΔS in equation (1), and sandbar monitoring that is concerned only with the measurement of ΔS_{high}. Monitoring of ΔS (total) is needed for long-term tracking of sediment storage; therefore, infrequent measurements (made every 3 to 10 years) of ΔS are acceptable. It is still not entirely clear how changes in low elevation sand correlate to change in high elevation sand in each reach. During normal dam operations, some high elevation sand is entirely disconnected from the river, whereas low elevation sand is always responsive to normal flow fluctuations. The purpose of mapping reaches with a return-interval of a few years is to provide these linkages in order to assess the effects of individual and cumulative HFEs. Establishing base maps of parts of the canyon as yet unmapped – even without a specified return date or return interval - is also important because several decades from now, only through mapping long reaches of the channel will an assessment of the long-term fate of sand in the Grand Canyon be made. This is because, given the accumulation of huge uncertainties in flux-based mass balance estimates (Project 2) over time scales of more than a few years, only with accurate bathymetric and topographic maps can we quantify multi-decadal changes in ΔS throughout the CRe (Project Element 3.2) in a meaningful way.

More frequent monitoring of ΔS_{high} (exposed sandbars) is required to provide timely resource information to stakeholders and managers and evaluate the effect of management actions. The time-series of sandbar volume and area established in the 1990s by Northern Arizona University (NAU), commonly referred to as the "NAU sandbar time-series", provides a long-term, historic context for the status and trends of a subset of sandbars. Because of the temporal richness of this data set, continued annual surveys of these sites will provide the only direct measurements of changes in sandbar size that can be compared to over two decades of measurements. Research and monitoring during FY13-14 that included repeat mapping of lower Marble Canyon suggests that the NAU sites provide a good representation of average sandbar condition for this reach (see also discussion below in project element 3.1.1). Yet measurements of the NAU sites alone do not represent a comprehensive monitoring strategy for sandbars, because these sites are most concentrated in lower Marble Canyon, and the degree to which observations at these sites can be extrapolated system-wide is still not fully understood. Thus, as part of the FY15-17 work plan, we intend to use repeat channel mapping (3.2) and remote sensing (3.1.2) to document system-wide trends in the sandbar population, develop methods for rapid sandbar surveys from camera images (3.1.3), and further our understanding of sandbar dynamics, towards a predictive capacity, using existing data (3.3). While a comprehensive sandbar monitoring plan has been an important goal of this project, a system as long and complex as Marble and Grand Canyons presents considerable challenges for developing a representative subsampling scheme, both spatially and temporally. Results from repeat channel mapping suggest that erosion and deposition of fine sediment on the bed and in eddies can by highly localized (Grams and others, 2013), and errors could be quite large if key portions of the channel are not monitored (Project 3.2). Insight gained over the last several years demonstrates that a comprehensive – or canyon-wide – assessment of the entire sandbar population from remote sensing and, where available, channel mapping is necessary to be confident in any monitoring scheme. Results from the analyses in FY15-17 outlined below will provide the foundation for a comprehensive sandbar monitoring plan using a combination of direct surveys and indirect photogrammetric and remote sensing techniques. In the paragraphs below, we outline the overall strategy of the sandbar monitoring program in this workplan. The monitoring components are described in greater detail in the description of each project element.

The established method for accurate and precise sandbar monitoring is conventional topographic survey (Hazel and others, 2010). While other methods have been evaluated (e.g. LiDAR and photogrammetry), they are equally (or more) expensive and, in the case of LiDAR, yield more resolution than is required. The topographic surveys are currently completed annually at 47 sites on a single non-motorized monitoring trip (element 3.1.1). This constitutes a relatively small sample of the more than 1300 large eddies in the CRe. This monitoring also includes measurements of campsite area at 37 sites. The monitoring program includes two elements designed to overcome this deficiency in spatial coverage. The remote sensing element (3.1.2) involves the analysis of aerial photographs collected at approximately 4-year intervals to provide an assessment of sandbar size in all large eddies in the CRe less frequently and at lower precision than the annual monitoring. The channel mapping project element (3.2) includes conventional topographic surveys at most large eddies in every river segment on a 3- to 10-year rotation (see Table 3). These two efforts each enhance the annual monitoring of NAU sites in different ways.

The primary purpose of the remote sensing images is to provide an assessment of all sandbars in the entire CRe at a single moment in time. This is, therefore, the only means to characterize statistically the entire population of exposed sandbars in order to evaluate data from any sub-sample. Additionally, measurements of sandbar area derived from the remote sensing images can be compared with measurements of sandbar area made from older aerial photographs taken as early as the 1930's.

The topographic measurement made during channel mapping surveys provide measurements for a large sample of sandbars using the same methods as the annual monitoring (see Figure 4). This provides data that can be used to statistically characterize a large population of exposed sandbars, at repeat intervals, in order to both evaluate data from any sub-sample at an instant in time, and also the ability of the annual monitoring to capture the essential aspects of change over multi-year periods. This is achieved by rigorously comparing response and site characteristics between the established monitoring sites and a much larger sample of sandbars in the same river segment, and by comparing the reach-scale change in sandbar volume over the period between repeat channel mapping efforts with the equivalent metric from the annual data. (see element 3.1.1, which includes an evaluation of the representativeness of sandbar monitoring sites in lower Marble Canyon).

Monitoring sandbars annually is adequate for long-term monitoring and for the evaluation of the combined effects of all management actions that occur over the course of a year, but is inadequate to evaluate the specific effects of individual management actions. For example, assessment of the effects of a single controlled flood for comparison with the effects of other controlled floods requires observations immediately before and after each event. To avoid costly repeat measurements around each controlled flood, we have been developing methods to monitor sandbars more frequently with remotely deployed cameras. This component of element 3.1.1 is expected to provide frequent (~monthly) measurements of sandbar size, albeit with less precision than provided by the annual monitoring.

Together, the sandbar monitoring project components of project elements 3.1.1, 3.1.2, and 3.2 (Table 1) provide (1) consistent monitoring of an established set of long-term monitoring sites on an annual basis, (2) less precise monthly monitoring for a subset of the long-term monitoring sites, (3) spatially robust assessments of sandbar size less frequently, (4) information on whether or not more (or fewer) sites are required to represent all sandbars in a given reach, and (5) information that will continually contribute to improved understanding of how the behavior of the established long-term monitoring sites represents changes outside that set of sites. Thus, we expect that each time we complete an analysis of either a remote sensing data set or a channel mapping data set, we will be better able to extrapolate from the limited number of sites monitored annually, at high precision and low cost but at low spatial coverage, to the state of sandbars in the entire CRe. During FY15-17 we will refine the remote sensing and photogrammetry techniques, and at the end of FY17, we will synthesize results of these different monitoring elements in a comprehensive analysis of sandbar changes across all the spatial and temporal scales for which data are available.

Table 1. Summary of sandbar and sediment storage monitoring efforts.

Project Element	Spatial Focus	Method	Measurement Frequency	Information Needs Met
3.1.1[†]	Selected high-elevation sandbars (47 sites)	Conventional topographic surveys (metric: volume and area)	Yearly	Annual status check on sandbar and camping beach condition
3.1.1	Selected high-elevation sandbars (42 sites)	Remotely deployed digital camera (metric: area)	Daily (metrics computed for 1 image per month)	Effects of individual management actions (controlled floods)
3.1.2	High-elevation sandbars systemwide (>1000 sites)	Remote sensing (metric: area)	Every 4+ years*	Long-term trend of sandbar size
3.2	High-elevation sandbars in 30 to 80-mile segments.	Conventional topographic surveys (metric: volume and area)	Every 3 to 10 years, depending on reach.	
3.2	Low-elevation fine-sediment storage in 30 to 80-mile segments.	Combined bathymetric and topographic surveys (metric: volume)	Every 3 to 10 years, depending on reach.	Long-term trend in fine-sediment storage

* Remote sensing images of the entire CRe were collected in 2002, 2005, 2009, and 2013.Frequency of future remote sensing missions is anticipated to be every 4 to 10 years.

†Project Element 3.1.3 aims to develop methods to increase the spatial coverage at the same measurement frequency and with possibly less precision.

D.2. Project Elements

Project Element 3.1. Sandbar Monitoring

Project Element 3.1.1. Monitoring sandbars using topographic surveys and remote cameras

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Objectives

1. Continue annual measurements of sandbars at long-term monitoring sites to track trends in sandbar area and volume for understanding sandbar dynamics.
2. Track annual trends in total campsite area at long-term monitoring sites with data from annual surveys.
3. Continue to document sandbar size on a daily timescale, by maintaining the network of autonomous remote-cameras.
4. Track monthly changes in sandbar areas at long-term monitoring sites by measuring areas using ortho-rectified images from the remote-camera network.
5. Complete the development of an interactive website to efficiently serve sandbar data and remote camera images with a user-friendly interface.

Hypotheses/Questions

1. What is the cumulative effect of HFEs and intervening dam operations on the size of sandbars in the CRe? *(relates to Section C.3, Question 1)*
2. What is the cumulative effect of HFEs and intervening dam operations on the size of campsites in the CRe? *(relates to Section C.3, Question 1)*
3. Do individual HFEs continue to build sandbars to a magnitude similar to that observed in response to previous HFEs? We hypothesize that the quantity of sand supplied by the Paria River and other tributaries is positively correlated with post-HFE bar volume *(relates to Section C.3, Question 2)*
4. How does sandbar size and shape prior to HFEs affect the bar-building response? *(relates to Section C.3, Question 2)*

Rationale/Justification

A subset of all sandbars and campsites located throughout the CRe will continue to be monitored annually using conventional ground-based topographic surveys. These surveys will contribute to the long-term NAU sandbar time-series. This is the longest, most accurate, and complete dataset describing the state of sandbars in the CRe. The monitoring program, initiated in 1990, includes surveys at 47 sites, which provides measurements of sandbar area and volume above the stage associated with a discharge of 8,000 ft^3/s. In addition, campsite area is measured at 37 of these sites. Methods for these surveys are described by Hazel and others (2008; 2010; in preparation) and Kaplinski and others (2009; *in review*). These annual surveys are supplemented by photographs of 42 sites, taken several times per day, using autonomous remote digital-camera systems (Bogle and others, 2012). These images make it possible to record the effects of changes in flow at a temporal precision that cannot be resolved by the annual topographic measurements.

Representativeness of the NAU sandbar time-series

The sites monitored in this project were selected based on the lengthy historical record, rather than a random selection from among all sandbars in the CRe. A key component of any monitoring program must include an evaluation of whether the sites selected for monitoring appropriately track changes in the resource of interest, in this case, sandbars and camping beaches. One of the objectives of the FY13–14 work plan was to evaluate the degree to which the sample average determined from measurements of the long-term monitoring sites represents changes of the population of all sandbars. Preliminary results from this analysis indicate that mean change in sandbar thickness (volume normalized by area) between 2009 and 2012, based on the 18 long-term monitoring sites in lower Marble Canyon (-0.06 m ± 0.06 m standard error), is consistent with the mean change among a much larger sample of 84 sandbars mapped in 2009 and 2012 by Project Element 3.2 (-0.06 m ± 0.04 m standard error) (Fig. 6).

While the NAU sites capture the mean response, they do not necessarily reflect the full range of sandbar responses, in particular those sites with large gains or large losses in the period from 2009 to 2012. Our analysis shows that the variance of thickness change between 2009 and 2012 among all sandbars is approximately double the variance among the 18 monitoring sites, indicating that the monitoring sites may tend to have smaller-magnitude changes than the collection of all sandbars. This suggests that, for lower Marble Canyon at least, our long-term monitoring may adequately represent mean sandbar condition, but fails to capture the full extent of variability in sandbar condition. The analysis also indicates that a random sampling of fewer than the current number of monitoring sites would be unlikely to capture mean bar condition better than the current monitoring sites (Fig. 6). This presents a challenge to our monitoring design, because monitoring sites are more frequent in lower Marble Canyon (about 1 site every 1.8 miles) than any other reach (1 site every 4 to 9 miles). Matching the monitoring site density in other reaches would require adding about 7 sites in upper Marble Canyon, 6 sites in eastern Grand Canyon, and more than 50 sites in east- and west-central Grand Canyon (RM 87-225).

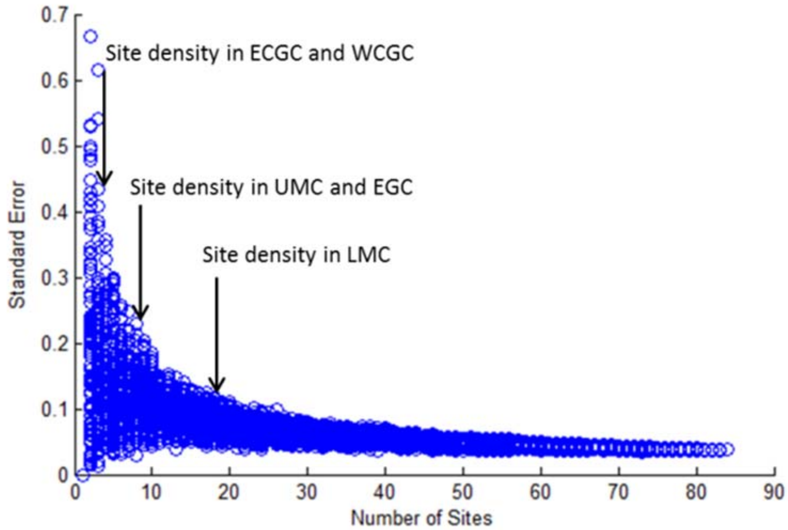

Figure 6. Bootstrap simulation of expected standard error (m) for estimates of sandbar thickness change as a function of sample size. Measurements of thickness change for 84 sandbars in lower Marble Canyon (data from Project 3.2) were sampled randomly using increasing sample size (1 to 84). For each sample size, 100 random selections of sites (numbering between 1 and 84) were made from among the 84 sites, and the standard error calculated and plotted. The standard error decreases quickly with increasing sample size up until n ~ 20. Standard error decreases more gradually thereafter. The sample site density in lower Marble Canyon (LMC) achieves a reasonable uncertainty for the number of sites. More sites would be required in east central Grand Canyon (ECGC), west central Grand Canyon (WCGC), upper Marble Canyon (UMC), and eastern Grand Canyon (EGC).

Improving the spatial resolution of the sandbar data set

Adding long-term monitoring sites would require additional and/or longer monitoring trips and an increase in the monitoring budget. Further, addressing the need for, and selecting the appropriate locations of, additional long-term monitoring sites will be greatly enhanced through project elements proposed in this workplan and through additional analysis of data from FY13–14. For example, we now have repeat channel mapping data for eastern Grand Canyon, and repeat mapping of upper Marble Canyon is proposed for FY16. These data sets will allow us to compare the response of the entire sandbar population from Lees Ferry to Phantom Ranch, to the response of the subset of sites in the NAU time-series, over multi-year periods (as above). Remote sensing and geomorphic mapping in Project Element 3.1.2 will allow us to compare coarser-resolution, but canyon-scale metrics of the total number and area of sandbars and eddies throughout the CRe, and allow us to compare how these metrics vary downstream. This type of canyon-scale information on the spatial distribution and size of each eddy and sandbar are necessary for a full assessment of the appropriate number of long-term NAU monitoring sites versus other types of sandbar monitoring, and an assessment of how these sites fit into the tiered monitoring approach to assess overall sandbar condition (section D.1).

There are also developing technologies that may allow us to increase the number of individual sandbars that can be surveyed, while adding relatively little effort to current field efforts. Thus, rather than adding additional long-term study sites to the NAU data set, we propose to evaluate alternative methods for surveying the topography of sandbars that have the potential to allow rapid and inexpensive measurement of a large number of sites (see Project Element 3.1.3). In addition, we propose to develop a sandbar model (see Project Element 3.3) that would predict the volume of sand in bars by incorporating information from the sandbar surveys, sandbars measured by remote sensing (Project Element 3.1.2), during channel mapping

(Project Element 3.2), and by rapid survey (if the method proves feasible) to estimate the status of the population of sandbars throughout Marble Canyon and eastern Grand Canyon. These efforts are focused on improving upon our annual estimate of sandbar size that is based on the topographic surveys conducted each fall, identifying shortcomings in the spatial distribution of NAU data set, and providing methods to assess sandbar condition across a range of scales.

Improving the temporal resolution of the sandbar data set

An additional objective of this project element is to improve upon the methods we use to estimate sandbar size change during short time periods, such as before and after an HFE. Currently, remote digital cameras capture images of nearly all of the monitoring sites several times per day. These images were made available on the GCMRC website following the 2012 and 2013 HFEs and have been used to make a rapid qualitative assessment of each sandbar response immediately after each HFE. It is also possible to use these images for more quantitative analyses; and we have made recent progress with the development of methods to measure sandbar area from these images, by ortho-rectifying each image using ground control points surveyed during monitoring trips. Ortho-rectification is the process of transforming an oblique image into an aerial photograph (rectification) which is geometrically corrected such that the photo has the same lack of distortion as a map ("ortho-"). We will continue to develop these methods with the goal of measuring sandbar response to each HFE and erosion rate following each HFE. Developing these methods involves: (1) measuring ground control points at all long-term monitoring sites that have cameras; (2) systematically evaluating the areal estimates from images using ground-based surveys carried out at the same time; and (3) developing unsupervised (fully automated) or partially supervised (minimal user input) methods to segment sandbars in ortho-rectified images, because manual segmentation of sandbars is slow and subjective. This will greatly improve upon our ability to compare the sandbar-building response to HFEs of different magnitude, duration, and sediment supply conditions.

Website access to the sandbar database

In 2014, we initiated the development of a sandbar database with a web-browser based user interface. We also implemented a rudimentary web-browser based interface for viewing selected photographs of monitoring sites following the 2012 and 2013 high flows. We will continue the development of these tools to allow users to view and download all photographs for each of the monitoring sites, in addition to completing a web interface for downloading and interactively visualizing the sandbar data (initially, sandbar areas and volumes).

Methods

Sandbar and campsite surveys will be conducted each fall using methods described by Hazel and others (2010) and Kaplinski and others (2014). One of the primary motivations for the sandbar monitoring is because they are used as campsites by visitors. The monitoring metrics of sandbar volume and area are related to campsite area (Hazel and others, 2010), but are not a direct measurement of campsite size. Two supplementary monitoring efforts are, therefore, included in this project to track changes in campsite size that are related to changes in sandbar topography and/or change in the extent of vegetation cover. The first of these project components are annual measurements of campsite area at 32 of the 47 sandbar monitoring sites conducted on the annual sandbar monitoring trip. The second component is observations and photographs for a collection of approximately 40 of the most popular recreational camping beaches between Lees Ferry and Diamond Creek. These observations are made by Grand Canyon River Guides through the "Adopt-a-Beach" (AAB) program. The methods for the proposed rapid surveys and modeling are described below under Project Elements 3.1.3 and 3.3, respectively. The novel methods that will be developed and used in this project element are those associated with the effort to quantify sandbar area and volume from the remote camera images.

Essentially, the process of estimating sandbar area from oblique images consists of ortho-rectifying the images using surveyed ground control points, delineation of the sandbar on each ortho-image, and then simply calculating the area. The ortho-rectification is an automated process that creates a mapping between ground and image coordinates, and warps the image such that pixels are located in the correct positions for the final image to be planimetrically correct. Ground control points were collected at a number of sites during FY13–14 in anticipation of applying this technique. The technique has been demonstrated using time series of images from the sandbars at RM22 and RM30. The sandbars have been delineated manually and verified using ground-based surveys; this process has already added hundreds of sandbar-area estimates using images collected in the past 5 years (Buscombe and others, *in prep.*). Our goal is to make the process of sandbar delineation from images as automated as possible, because the process must be repeated many times at each of the monitoring sites. To this end, initial trials using a variety of image processing methods have been encouraging, and we are confident that accurate, automated delineation of sandbars from images is feasible. This technique has the potential to significantly augment data on subaerial sandbar areas at minimal extra cost.

We have recently demonstrated that sandbar volumes can also be estimated from digital elevation models (DEMs) constructed directly from ortho-rectified digital imagery collected by autonomous cameras (Buscombe and others, in preparation). If the elevations of water lines in images are known, contour maps of sandbars can be constructed as the flow varies. The process consists of obtaining the horizontal coordinates of waterlines from the rectified image, and assigning the vertical coordinate from the estimated water stage. As the stage varies, a DEM can be constructed from several contour lines. The process works best if stage varies significantly over short periods, such as the upramp and downramp periods of controlled floods. Stage elevations are either measured using an instrumented record (such as a pressure transducer) or estimated using a stage-discharge relation that exist for all long-term monitoring sites (Hazel and others, 2006). The technique has been evaluated using imagery from the RM30 sandbar during the 2012 and 3013 HFEs. The DEM constructed using imagery from the 2012 HFE was validated using data collected at that site immediately afterwards using conventional ground-based surveys. We propose to apply the technique to more sites to obtain volumetric estimates of bars after HFEs, as a cost effective means with which to assess the effects of HFEs on sandbars.

Annual Products

- Update on sandbar area and volume and campsite area based on monitoring from the previous year.
- Annual monitoring data made available on website within 6 months following data collection
- Photographs showing effects of HFEs made available on website within 2 months following data collection.

Outcomes and Products – FY15

- Web browser interface for viewing remote camera photographs.

- Web browser interface for viewing sandbar data.
- Journal article detailing and evaluating methods for measuring sandbar areas and volumes from remote camera images *(lead author Buscombe)*.

Outcomes and Products – FY16

- Sandbar data and photographs updated on web interface.
- Report/journal article on sandbar response to HFEs or short-term sandbar variability based on measurements of sandbar size derived from remote camera images *(lead author Tusso).*

Outcomes and Products – FY17

- Report/journal article on long-term trends at the sandbar monitoring sites (joint product with 3.1.4 and 3.2) (*lead author Hazel*).
- Report (written in conjunction with other listed project elements) evaluating the current monitoring scheme using the long-term high-resolution NAU time-series (3.1.1), more spatially robust channel mapping (3.2) and remote sensing (3.1.2), and new techniques incorporating remote camera ortho-rectification and structure from motion (3.1.3) (*lead author Grams*)

Project Element 3.1.2. Monitoring sandbars and shorelines above 8,000 ft^3/s by remote sensing

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Paul Grams, Research Hydrologist, USGS/GCMRC
Thomas Gushue, GIS Coordinator, USGS/GCMRC
Ted Melis, Physical Scientist, USGS/GCMRC

Objectives

1. Objective 1 is to measure the area of exposed sand above the elevation of the 8,000 ft^3/s stage (high-elevation sand) for more than 1300 large eddies (henceforth referred as the "large eddy dataset") using imagery acquired from the remote sensing overflight in May 2013. The objective is also to compare the results from mapping sand area on the 2013 images to sand area measured on the May 2002 and May 2009 overflight images (Ross and others, in preparation).
2. Objective 2 is to evaluate changes in sandbar topography (elevation and volume) between 2002 and 2013 at the same set of more than 1300 eddies monitored for changes in sand area using digital surface models (DSMs) from automated photogrammetry that are acquired coincident with overflight imagery.
3. Objective 3 is to use results from Objectives 1 and 2 to investigate the representativeness of the smaller set of the NAU sandbar time-series that are monitored with detailed topographic surveys (Project Element 3.1.1). Investigation of the representativeness of the NAU sandbar time-series is a key component of Project Element 3.1.1 and the collective set of sandbar monitoring efforts as a whole (described in Table 1). The results of Objectives 1 and 2 are synoptic censuses of the population of sandbars in the CRe that is independent and spatially robust relative to relative to the detailed surveys of the smaller set of NAU sandbar time-series. Objective 3 complements, for example, the

analysis (Fig. 6) that was based on a smaller set of sandbar surveys for one 30-mile river segment with an analysis using the remote sensing censuses of sandbars. Objective 3 is also useful for other projects, and specifically identifies the extent to which the periodic remote sensing overflight measurements of sandbar area and topography for a large portion of the Colorado River can be used to inform the groupings of sandbars by morphology and flood response proposed in modeling work of Project Element 3.3.

4. Objective 4 is to complete a geomorphic base map for all of Grand Canyon. The geomorphic base map is necessary to this and other projects that require information about the canyon-wide distribution and characteristics of eddies and sandbars or other types of geomorphic units, such as debris fans and gravel bars that provide important shoreline habitats for aquatic organisms and riparian vegetation. Objective 4 provides geomorphic units to assess: i) variability observed in sandbar area and topography population data in Objectives 1 and 2, ii) representativeness of other monitoring efforts and sites investigated in Objective 3 and Project element 3.1.1, and iii) groupings of sandbars by morphology and flood response proposed in modeling work of Project Element 3.3

Hypotheses/Questions

1. How much exposed sand is present in 2013 compared to 2002 and 2009 throughout Marble and Grand Canyons? *(relates to Section C.3, Question 1)*
2. How has sandbar topography changed from 2002 to 2013 throughout Marble and Grand Canyons? What is the accuracy and uncertainty of the aerial overflight-based measurements of sandbar topography when compared to measurements of topography from other monitoring efforts? *(relates to Section C.3, Question 3)*
3. Can the more spatially extensive set of sandbar measurements derived from the aerial overflight data be used to i) better understand the ways in which the long-term monitoring sites are and are not representative of sandbars throughout the larger river corridor?, and ii) produce a larger data set of sandbar size and morphology useful for Project 3.3. In the latter case, the remotely-sensed data can be used to develop more robust groupings of sandbars by morphology (using metrics such as area, volume, slope, planform shape, and concavity) and as a validation data set for a generalized sandbar response model calibrated using the NAU sandbar time-series. *(relates to Section C.3, Questions 1 and 3)*

Rationale/Justification

Sandbars in the CRe downstream from Glen Canyon Dam are formed in eddies that typically occur in the lee of boulder debris fans. Debris fans constrict the river channel and form the eddies that are slower velocity and act as “traps” at hundreds of locations for finer sediment transported as suspended load (Schmidt and Rubin, 1995). Existing digital imagery and topographic data collected from remote sensing overflights in 2002, 2009, and 2013 are used to inventory and document both large- and small-scale sandbar and shoreline changes within eddy areas during this period. Because only a subset of sandbars are surveyed using conventional methods (Project Elements 3.1.1 and 3.2), the purpose of analysis of these remote sensing data is to track the area of exposed sand above the elevation of the 8,000 ft^3/s stage (high-elevation sand) of 1300 large eddies along the Colorado River. The remote sensing images remain the only way to produce a census of the condition of sandbars synoptically in Glen, Marble, and Grand Canyons.

Prior to completing new analysis of remote sensing images, a geomorphic base map is required to provide context for this and other system-wide studies in the CRe. The map is of immediate need for ongoing system-wide studies of sandbars and riparian vegetation. The map will consist of just a few simple map units such as: eddies; sand deposits within eddies; sand deposits along channel margins (not within eddies); debris fans; gravel bars; talus; and bedrock. This will enable any system-wide analyses to be segregated by geomorphic setting. While previous studies have completed detailed maps including these features for short segments (e.g. Hereford, 1996; Hereford and others, 2000; Schmidt and others, 2004) or systemwide inventories of specific resources, such as eddies that contain backwaters (Grams and others, 2010), there does not exist a map that covers the entire CRe with a consistent set of map units and mapping criteria.

In the FY13–14 work plan, regions historically containing exposed sand above the elevation of the 8,000 ft^3/s stage (high-elevation sand) were delineated for more than 1300 large eddies along the Colorado River in imagery acquired in 2002 and 2009. The classification of the areas of sand exposed in these large eddies in the 2002 and 2009 imagery will be completed in FY14. In this project, we will extend the record of canyon-wide sand area assessment to include analysis of overflight imagery acquired in 2013.

Imagery from 2002, 2005, and 2009 has also been incorporated in an analysis of sandbar area change within six reaches in which high-elevation sand was mapped from images taken in 1965, 1973, 1984, 1990, March 1996, and April 1996 (Schmidt and others, 2004) (Fig. 7). These

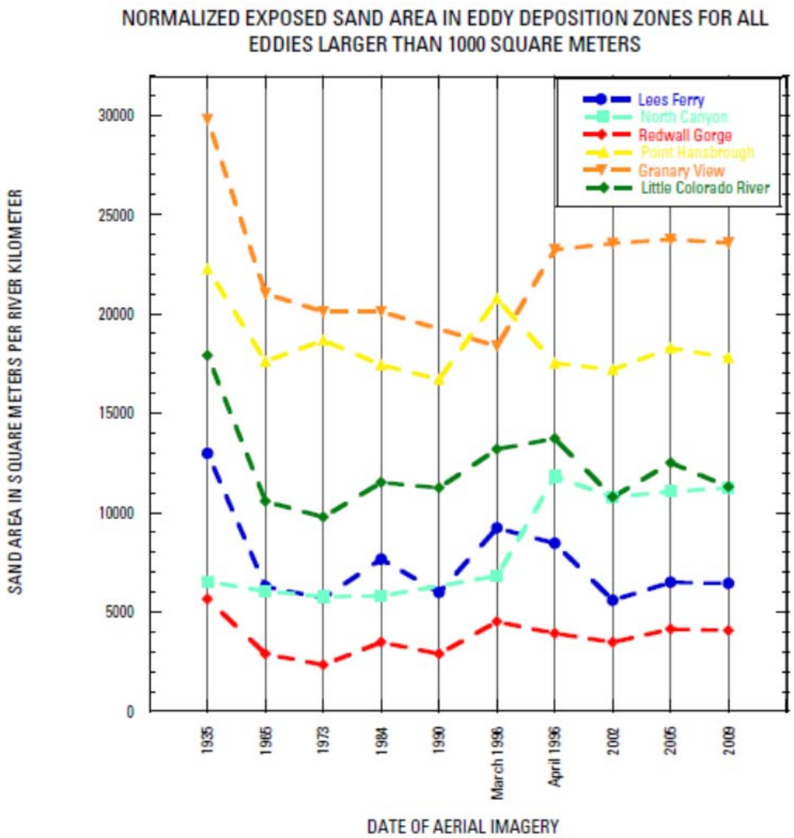

Figure 7. Area of sand in square meters per km in eddy deposition zones for all reaches with historical data from 1935 to 2009.

estimates of sandbar area were reasonably accurate with respect to independent ground truth estimates derived from more detailed topographic surveys; the area estimates under- or over-predicted survey-derived estimates by 3-15 percent in the reaches analyzed. The results show that the area of sandbars exposed above the 8,000 ft^3/s stage in Marble Canyon was generally larger in images from the era of post-dam controlled floods (April 1996, May 2002, May 2005, and May 2009) than in images from the post-dam period before controlled floods (June 1990 and March 1996). From 2002 to 2009, sandbar areas, on average, were estimated to be lowest in 2002, greatest in 2005, and intermediate in 2009. Sandbar areas appeared to potentially vary as a function of time since a controlled flood (HFE); the 2002 imagery were collected 6 years after an HFE, the 2005 imagery were collected 6 months after an HFE, and the 2009 imagery were acquired 1 year after an HFE. Results of this work will be delivered and summarized in a manuscript prepared by the end FY14 (Ross and Grams, *in prep.*).

Recent analysis of digital topography from the 2002 and 2009 aerial overflights relative to ground truth of detailed topographic surveys demonstrates the feasibility and limitations of measuring topographic changes with data from overflights that are less accurate. Table 2 shows examples of the average error in estimates of sandbar elevations derived from overflights relative to survey data for cross-sections at 5 different sandbar monitoring sites. Changes measured between 2002 and 2009 with the overflight data had a root mean square error (RMSE) of 0.49 m when compared to the ground truth data of changes measured from topographic surveys. These results provide conservative estimates of the uncertainty associated with topographic change detection conducted with the overflight data and the magnitude of change that might be reliably detected with the overflight data. On average, the correlations between elevations and changes in elevation measured from the overflight and survey data were moderate to strong. When compared with the magnitude of changes in elevation observed with the detailed topographic surveys (Fig. 8) the average error estimates (Table 2) indicate that the overflight data are most useful for detection of large topographic changes. Similar uncertainty analyses and error budgets for sand volume, area, and other morphological characteristics of bars will need to be performed in the course of the work proposed for this project. Nonetheless, the potential for synoptic measurements of sandbar topography within the level of uncertainty in elevation indicated in

Table 2. Average error and correlation between elevation measurements from total station survey and DSMs acquired in 2002, 2009, and change detected with each method from 2002 to 2009 at five sandbar study sites.

Site	Year	RMSE (m)	R^2
44L	2002	0.20	0.87
	2009	0.38	0.91
	2002-2009	0.33	0.73
68R	2002	0.59	0.24
	2009	0.90	0.73
	2002-2009	0.67	0.03
93L	2002	0.53	0.70
	2009	0.26	0.97
	2002-2009	0.71	0.86
122L	2002	0.18	0.93
	2009	0.39	0.92
	2002-2009	0.43	0.74
194L	2002	0.22	0.99
	2009	0.20	0.98
	2002-2009	0.31	0.84
Average	**2002**	**0.35**	**0.75**
	2009	**0.43**	**0.90**
	2002-2009	**0.49**	**0.64**

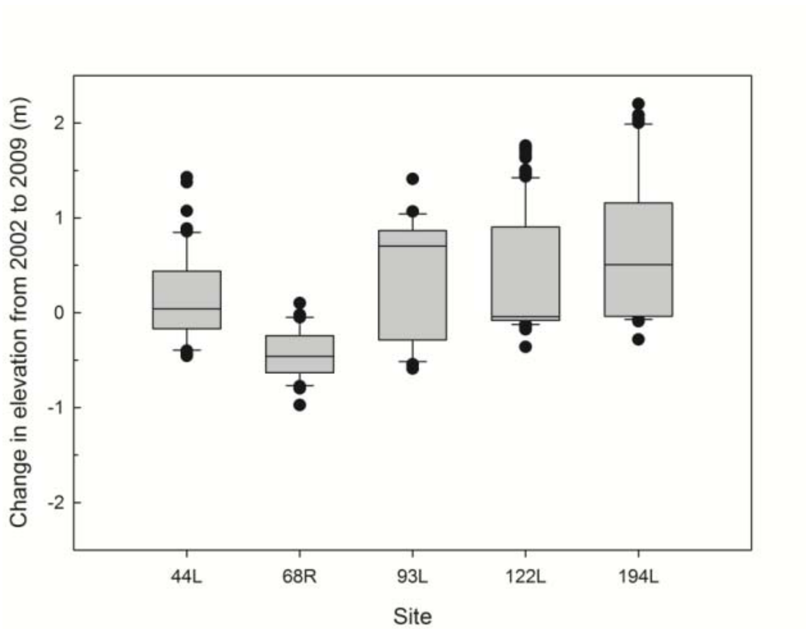

Figure 8. Box plots showing distribution of changes in elevation determined from total station surveys in 2002 and 2009 at five sandbar monitoring sites.

Table 2 suggests that these remote sensing data have utility for better understanding the ways in which the long-term, sandbar survey monitoring sites are and are not representative of sandbars throughout the larger river corridor. Further, these data can be leveraged in Project Element 3.3. as both an additional data set to define sandbar groupings by morphology (using metrics such as area, volume, slope, planform shape, and concavity) and as a validation data set for a generalized sandbar response model.

Methods

Mapping sandbar area

The new work proposed in this project will extend analyses conducted on the 2002 and 2009 imagery to include measurements of sand area in imagery acquired in the 2013 overflight. The canyon-wide remote sensing data used in this effort consists of four-band, ortho-rectified digital imagery (blue, green, red, and near-infrared bands) acquired in late May 2013. The remote sensing effort will involve a landscape delineation of four units: water, vegetation, sand, and other bare (non-vegetated) terrestrial surfaces. This will be similar to the landscape databases in production for image data sets collected in 2002 and 2009. For each image set, the water surface and total vegetation are mapped using interactive image processing algorithms (Davis and others, 2002; Ralston and others, 2008). This project will use water and total vegetation classifications produced for the 2013 imagery in riparian vegetation-related project work that is currently proposed for FY15 (see Project 11.2). Following the water and vegetation classification, areas of sand will be classified. Therefore, the sand area classification and measurements proposed here will commence in FY16 and proceed into FY17. We will report on the results of the mapping and change analyses will be reported on in FY17.

Measuring topographic changes and evaluating representativeness of long-term survey dataset

Digital surface models (DSMs) were produced from airborne automated digital photogrammetry data acquired during the aerial overflights of 2002, 2009, and 2013 for the 450 km length of Glen and Grand Canyon at steady Colorado River discharge of 8,000 ft^3/s (Davis, 2012). The airborne automated digital photogrammetry DSM data acquired in 2002 and 2009 have been evaluated during work recently completed in 2013 and 2014 by Phil Davis (personal communication). The DSM data have 1-m cell resolution with vertical ellipsoid heights reported to the nearest 10 cm (but only accurate to the nearest 30 cm – see following explanations and example of error assessment for the 2009 data), and are sectioned into U.S. Geological Survey map quadrangles. The data were not initially processed to remove effects of vegetation or other surface cover on topographic elevation values. However, work completed in 2013 and 2014 developed a methodology to minimize these effects that was tested on the 2009 dataset, in which pixels that contained vegetation canopies identified in classification of the coincidentally collected and co-registered multispectral imagery were replaced with elevations interpolated from surrounding bare ground surfaces.

Horizontal and vertical accuracy of the 2002 and 2009 DSM data were assessed by comparison with 125 ground control points distributed over the entire 450 km length of data collection (Davis, 2012; P. Davis, USGS, pers. comm., 2013). Errors for the 2009 dataset were normally distributed with an initial 38 cm vertical offset, but were adjusted resulting in a final dataset with relative vertical RMSE of 30 cm (59 cm at 95 percent confidence level with 1.96 sigma) (P. Davis, USGS, pers. comm., 2013). The relative positional (horizontal) accuracy was determined to be 19 cm (47 cm at 95 percent confidence level with 2.45 bivariate sigma) (Davis, 2012).

For this work, we will conduct change detection using the digital topography (DSM) data from 2002, 2009, and 2013 images. The change detection will be completed for sandbars in the same set of more than 1300 eddies monitored for changes in sand area. The datasets will be differenced and vertical and volume changes will be estimated for the areas of sand mapped in the large eddies that are the focus of Objectives 1 and 2. Changes that are detected in these areas will be evaluated relative to ground truth, as available, from the subset of sandbars that are topographically surveyed (e.g., Table 2).

The distribution of volumes and areas of sandbars for the 3 overflight dates as well as the distribution of changes between these dates will be compared to respective distributions of data derived from the smaller set of surveyed sandbars. The comparison of distributions will be instrumental in completing the third objective that aims to investigate the representativeness of the long-term NAU sandbar data set relative to the populations of sandbars that are located throughout larger segments of the river. For example, we may expect that the total number of eddy sandbars, as well as the area- or volume-based distribution of sandbars (e.g. Fig. 6), will vary among geomorphic reaches (e.g. Schmidt and Graf, 1990; Melis, 1997), among those 30-80 mile segments in which high-elevation sandbars are monitored with conventional topographic surveys every 3 to 10 years (Table 1, and Element 3.2), and collectively within the greater river corridor between Glen Canyon Dam and Lake Mead. Additionally, the representativeness of the long-term NAU sandbar data set is vital to the sandbar modeling component of this work plan (Project Element 3.3) For example, are sandbar groupings and eddy characteristics derived from the NAU sites appropriate for understanding eddy sandbar behavior in the 1300 eddies measured in this project? Does an empirical model of sandbar response calibrated from the NAU sandbar data represent a viable approach for modeling sandbars system-wide? Practically, these questions can only be answered on a scale as large as the Grand Canyon using data on sandbar characteristics and change derived from remote sensing, which provides us measures of the true (system-wide) sandbar population.

Geomorphic base map

The geomorphic base map will be constructed by identifying contacts between each of the map units and digitizing those lines on-screen in ArcGIS. The initial interpretation and mapping will be done in the office using recent (2009) aerial imagery as a base. The preliminary mapping will followed by field checking areas of uncertainty on the annual sandbar monitoring trip in Fall 2015, requiring no additional logistic costs. Grams (unpublished data) has completed a preliminary base map for lower Marble Canyon (Fig. 9) for use in the channel mapping project (FY13–14 Project Element A.2).

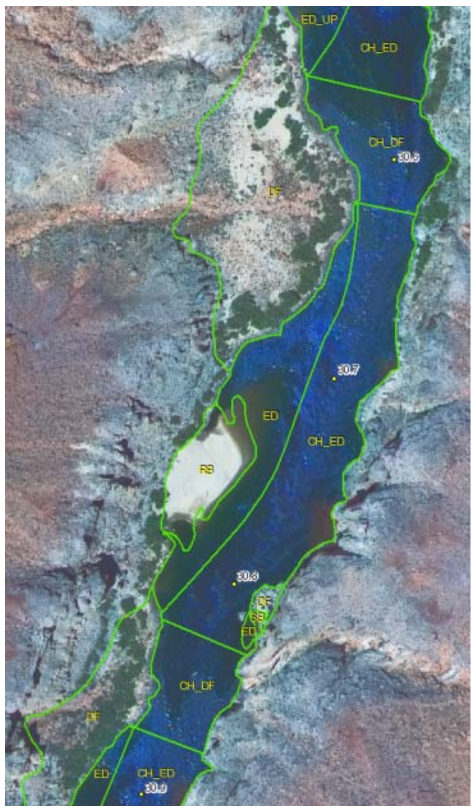

Figure 9. Example geomorphic base map for a segment of lower Marble Canyon showing channel segments (CH_*), eddies (ED), sandbars (RB, SB), and debris fans (DF).

Outcomes and Products – FY15

- Completed geomorphic base map documented in USGS report *(Ross leads with collaboration from Sankey and Grams).*

Outcomes and Products – FY16

- Completed high elevation sand area map from 2013 imagery

Outcomes and Products – FY17

- Report or journal article on system wide variability and changes in sandbar area, sandbar elevation, and sandbar morphology from remote sensing, 2002–2013 *(Ross leads with collaboration from Sankey and Grams)*
- Report (written in conjunction with other listed project elements) evaluating the current monitoring scheme using the long-term high-resolution NAU time-series (3.1.1), more spatially robust channel mapping (3.2) and remote sensing (3.1.2), and new techniques incorporating remote camera ortho-rectification and structure from motion (3.1.3)

Project Element 3.1.3. Surveying with a camera: Rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry

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Paul Grams, Research Hydrologist, USGS, GCMRC
Graduate Student

Objectives

The objective of this work is to develop and evaluate a methodology which allows low-cost and rapid (in terms of data collection and processing) monitoring of sandbars with a camera, implemented to support monitoring and geomorphic change detection. To this end, the use of a photogrammetric technique called 'Structure-from-Motion' (SfM), which builds an accurate three-dimensional model of a scene from photographs taken from multiple viewpoints (James and Robson, 2012; Westoby and others, 2012; Fonstad and others, 2013), will be evaluated for the purposes of repeat mapping the topography of sandbars and cultural resource sites. This is a proven method; however, there are a number of considerations for generalized implementation at any site. We propose to thoroughly evaluate errors and uncertainties, as well as the logistical considerations for efficient field data collection and data processing, towards the intended outcome of a set of sampling and data-processing protocols for the creation of a DEM of any location within the river corridor from a set of photographs taken using any non-specialist camera.

If the above objectives are completed, a further objective would be to develop 'citizen science' tools that would allow river guides or other members of the public to contribute to sandbar mapping efforts simply by taking a set of photographs following a prescribed protocol. The SfM technique would eventually be used to create DEMs of 100s of sandbars to augment and evaluate the representativeness of the 45-50 long-term NAU sandbar time-series (see hypotheses/questions below).

Hypotheses/Questions

1. Can accurate digital elevation models (DEMs) be obtained rapidly, with quantification of errors and uncertainties, and with minimal logistical support, using a consumer-grade handheld digital camera? If so, what are the limitations of this technique relative to traditional total station surveys and what is the accuracy of these image-derived DEMs compared to total-station-derived DEMs? We hypothesize this is possible using Structure-from-Motion (SfM) photogrammetry, with comparable resolution to traditional total-station derived surveys. *(relates to Section C.3, Question 1)*

2. Can a simple protocol for photographing any sandbar be drawn for a non-specialist, which would result in a set of images sufficient to create a DEM of that sandbar using SfM? We hypothesize that experimental trials with the SfM technique using field and laboratory data should be sufficient to establish a set of guidelines on image collection for a non-specialist. *(relates to Section C.3, Question 1)*

Rationale/Justification

This research will, generally, establish a viable method for rapid, accurate, and low-cost topographic mapping of any location within the river corridor, and specifically, augment the data from, and inform sampling strategies for, long-term sandbar monitoring. The long-term time series of sandbar areas and volumes at select sites throughout Grand Canyon is a vital resource for examining the long-term health of sandbars and the impacts of management strategies. Such time-series can be used to assess the effectiveness of individual management strategies such as controlled floods, develop data-driven models for sandbar behavior, and monitor campsite quality and area through time.

The set of 47 sandbars measured annually by topographic survey is a small sample of the more than 1300 large eddies in the CRe, and is potentially biased towards larger, more stable, sites. Recent efforts to evaluate the representativeness of sand volumes derived from these bars have indicated that the established long-term monitoring sites may adequately represent mean sandbar volume in lower Marble Canyon for some time intervals, although the variance is inadequately represented by the set of long-term monitoring sites. Because of this, and because more monitoring sites are located in lower Marble Canyon than other reaches, it is likely that the frequency of monitoring sites in lower Marble Canyon is a minimum. Therefore, there remains a pressing need to develop a representative sandbar sampling design. Our analysis suggests that up to 60 additional sites could be required to achieve the same frequency of monitoring sites in all parts of the CRe (see Project Element 3.1.1). Thus, the primary motivation for this project is to develop methods for measuring sandbars that would enable an increase in the number of bars monitored without a corresponding increase in field effort and expense. In practical terms, this means testing whether it is possible to survey any given exposed sandbar in approximately 20-30 minutes in the field, as opposed to 3 to 6 hours in the field per bar with traditional methods. An additional motivation for developing a rapid surveying method is to have a means to acquire data from a range of sites (and times) outside those monitored on an annual basis, in order to, for example, 1) investigate what (if any) metrics derived from a given sandbar DEMs or time-series of sandbar DEMS could be used as indicators for sandbar state (health) and persistence; and 2) to provide more data to aid statistical grouping of sandbars with similar dynamics, which would greatly help in the concurrent development of a predictive sandbar model (see Project Element 3.3.).

Having a means by which to rapidly map any sandbar, at any time during daylight, using non-specialist equipment (a consumer-grade camera) would be an extremely useful tool with which to augment current sandbar mapping activities with minimal cost. The use of remote cameras to estimate sandbar areas (Project Element 3.1.1) is limited in scope to the specific sites at which these cameras are installed, and the specific time at which the photograph is taken (which needs to be programmed into the camera system in advance). The use of the remote-camera imagery to construct a sandbar volume (above a given stage) also requires large fluctuations in flow. The SfM technique, in contrast, could conceivably be used at any site to map sandbar volume of the subaerial portion of the bar at that time. Monitoring certain sites with greater frequency would find several applications at the event-scale, such as monitoring bar slumping processes, erosion due to boat wake, or during experimental high flows. For example, how does generalized sandbar morphology differ as a result of high flows with different hydrograph shapes (magnitudes, durations and asymmetries)? Specifically, how does downramp rate affect sandbar slope? Answering this question requires more frequent topographic data (i.e. multiple DEMs associated with different downramp rates) from sandbars at sites with a range of hydraulic and geological settings, hitherto unobtainable through conventional methods, which will be addressed with the SfM technique.

The method we propose to evaluate is a photogrammetric technique commonly known as *Structure-from-Motion* (SfM). The SfM technique is a method for constructing a 3-dimensional surface (map) from a set of oblique photographs of the same area taken from different perspectives. The method is so-called, because the 3D position (structure) of features present in multiple images can be recovered from acquiring imagery by moving the camera relative to the scene (motion) so that multiple perspectives are achieved. The process is also able to render the images onto the DEM to create a DSM (Digital Surface Model, which in this case is a DEM overlain with the image pixels in the correct 3D location) which could be invaluable for mapping useful attributes other than elevation that are not obtainable using conventional surveying techniques, such as vegetation (from image color), and even grain-size estimates of the sediment surfaces (from image texture, using techniques similar to Black and others, 2013). The algorithms for processing the images exist and are available in commercial software: the purpose of this project would be to implement those existing techniques using that software, evaluate the products (DEMs) with conventional survey techniques (Wheaton and others, 2010), and develop a work flow to facilitate implementation of the technique to monitoring sandbars in the CRe.

Methods

The majority of the work will be carried out by a graduate student at Utah State University under the primary supervision of Joseph Wheaton, with co-advisement by Paul Grams and Daniel Buscombe of the USGS/GCMRC. The student will familiarize him/herself with powerful, and expansive (scriptable), commercial SfM software (e.g. Agisoft Photoscan) as well as open-source software implementations of SfM (e.g. VisualSfM); carry out a number of trials in controlled conditions in order to assess the accuracy and precision of digital surface models; and develop protocols for photo collection such as, but not limited to, (1) the number and angular spread of images; (2) the requirements for vantage and perspective; (3) the degree of overlap between images; (4) the minimum amount of ground control points required, and (5) the effects of light conditions and surface textures on the photogrammetric solution. Some of these issues have been discussed in a general sense by recent articles in the geomorphology literature (for example, James and Robson, 2012; Westoby and others, 2012; and Fonstad and others, 2013) but the specific requirements and sensitivities for landforms with the range of scales of sandbars would need to be addressed.

The student will then systematically photograph sandbars in Grand Canyon during annual sandbar monitoring trips, during which time the same bars will be mapped using conventional total station surveys, which are highly accurate but low in spatial resolution (of the order 1 measurement per several square meters). SfM provides point clouds at or near the spatial resolution of the photographs that, depending on factors such as the camera specifications, and the range to the objects in the scene, is of the order tens to thousands of measurements per several square meters. Therefore, SfM-derived DEMs need to be down-sampled in order to compare with total-station-derived DEMs. To quantify the accuracy of SfM at its native resolution, a subset of bars will also be surveyed using ground-based LiDAR (up to millions of measurements per several square meters). These data will then be down-sampled to the average resolution of the SfM-derived DEMs. These data will be worked up into image-derived and conventional DEMs, and the accuracy of the SfM technique for sandbars will be assessed through extension of surface uncertainty estimation techniques in the GCD software. The precision of DEMs from the SfM technique will be assessed by comparing DEMs of the same sandbar(s) using different sets of photographs collected in the field.

Photographs will be collected at a sufficient number of sites to represent a range of sandbar types and settings encountered in Grand Canyon. This will include sites in wide and narrow reaches, sites with dense and sparse vegetation, and sites with different sandbar morphology. We anticipate this will include analysis of at least 8-10, and possibly more, different sites. In addition, we will collect photographic data and produce SfM-derived DEMs for at least 1 or 2 cultural resource sites. These data will be used by scientists in Project 4 for comparison with data collected by ground-based lidar.

One potential challenge associated with photogrammetric mapping of sandbars in Grand Canyon is the effect of strong sunlight and shadows, which may limit the success of SfM at pixel matching in areas of low contrast. This will be tackled directly by collecting images of the same bar from the same locations at several times during the same day. Another problem will be obtaining sufficient vantage to photograph from, so each bar will be photographed from a number of different relative elevations and viewpoints. The sensitivities of the technique to factors such as the number of images and angular spread of camera positions (the collective noun for these factors we term, the scene geometry) will be assessed by creating a DEM for each permutation of photographs of a scene in a collection, then organizing DEM errors (relative to a benchmark data set obtained by total station and/or LiDAR) by each factor in the scene geometry. Each set of images will be worked up and their accuracy assessed reference to benchmark data (e.g. total station and ground-based LiDAR surveys). To address the potential issue of insufficient image texture over the smoothest surfaces, the texture of these surfaces will be enhanced using a number of standard camera settings and image processing algorithms designed to enhance image contrast.

Outcomes and Products

- Developoment of SfM sampling protocol
- Development of SfM extensions to GCD and existing SfM software, as well as stand-alone software required to facilitate efficient post-processing of imagery and change detection analysis.
- Report/journal article on application of the SfM method to measuring sandbar topography (*lead author Graduate Student*).

Project Element 3.1.4. Analysis of historical images at select monitoring sites

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Thomas Gushue, GIS Coordinator, USGS, GCMRC
Robert Weber, Photogrammetrist, Pinnacle Mapping Technologies, Inc.

Objectives

1. Extend sandbar area and volume long-term monitoring measurements to include data points from 1984 for a select set of sites.
2. Interpret the sandbar area and volume measured from photogrammetrically-derived topography with regard to unplanned floods that occurred in 1980, 1983 and 1984, and in the context of sandbar response to HFEs since 1996.
3. Incorporate completed 1984 sandbar data into sandbar database and interactive website (Project Element 3.1.1).

Hypotheses/Questions

1. To what extent were sandbars larger in area and volume following the largest magnitude and longest duration post-dam floods (the 1983-84 floods) than following recent HFEs? *(relates to Section C.3, Question 2)*
2. What can the 1984 post-HFE area and volume measurements for a select set of sites inform us about sandbar behavior? *(relates to Section C.3, Question 3)*
3. Can analysis of digital photogrammetry improve our understanding of sandbar change over time and improve analysis of the long-term monitoring record? *(relates to Section C.3, Question 1)*

Rationale/Justification

Our understanding of the long-term trends in sandbar size and abundance is limited by the lack of detailed measurements made before the era of environmental management that began in the CRe in 1990. Our understanding of resource responses prior to the current sandbar monitoring efforts is based on limited observations of sandbars following the floods of 1983-86 (Schmidt and Grams, 2011). However, those generalizations of sandbar behavior are based largely on imprecise photo comparisons and are not quantitatively tied to the current sandbar monitoring program. The purpose of this research activity is to extend the temporal monitoring record for the long-term sandbar monitoring sites (Project Element 3.1.1) by incorporating data from aerial photography taken before 1990. In FY13–14, we investigated the possibility of extending the long-term sandbar monitoring record (Project Element 3.1.1) by ortho-rectifying historical aerial images acquired in October 1984 for a selected set of sites. These images were used to create a three-dimensional topographic surface using digital photogrammetry technologies and software.

The feasibility of using digital photogrammetry to ortho-rectify photographs and generate digital elevation models (DEMs) of sandbars in Grand Canyon was initially examined by Blank (2000) and O'Brien and others (2000). At the time, the computer-based software and technologies did not result in photogrammetric surfaces sufficient for detecting change in sandbar elevation of less than 25 cm. Recent advances in photogrammetry computer software and high accuracy digital scans made from the original negatives collected during the aerial overflights have made digital terrain extraction economically feasible and with uncertainties more appropriate for change detection and comparison with historical sandbar surveys made during the 1990s and 2000s. Thus, this project element builds on the work of Blank (2000) and O'Brien and others (2000) and utilizes improved methods to derive topography for selected sandbar study sites in Glen, Marble, and Grand Canyons.

In FY13, digital terrain extraction and analysis of the results were made at 8 study sites. These results were presented at the Annual Reporting Meeting in January 2014. The DEMs generated from the 1984 images have a surface uncertainty of 25 cm or less. Thus, we can confidently use the DEMs to determine sandbar volume and area using similar methods for that of the NAU sandbar monitoring project. This has been accomplished at 7 of 8 study sites. Initial findings are that sandbar area and volume above the stage elevation of 8,000 ft^3/s was greater in 1984 than that measured in 2013 at 4 of the 7 sites. One sandbar (the Saddle Canyon site at RM 47) was 70 percent greater in area and volume in 1984; the other sites were 10 to 50 percent greater in size. The remaining sites were smaller in 1984 than present. While the sample size is small, these results are encouraging for temporal extension of the sandbar monitoring time series to 1984, as well as other years of interest. These results only provide tentative support for the hypothesis that sandbars were larger in 1984 than present, as almost half of the bars analyzed were smaller compared to present. Analysis of additional monitoring sites is required to provide a more complete picture of sandbar size following the 1980s floods for comparison with sandbar size following recent HFEs.

In order to determine the accuracy of the photogrammetrically-derived volumes, we are currently investigating a method that will allow us to better test the image-derived DEMs against actual ground surveys for four of the long-term monitoring sites previously processed in FY13. Because there have not been independent topographic surveys made with conventional methods at the same time as the collection of aerial photography, it is important that the same methods developed in FY13–14 be applied to photographs taken within a week or two of a total station sandbar survey. This would allow determination of the elevation and volumetric error associated with the techniques utilized in the study. We have identified two possible photography datasets with which to make this comparison: May 1994 and September 1996. Both data sets meet the requirements needed to be usable for comparative purposes as they were collected at scales similar to the October 1984 film (1:4800 vs. 1:3000), and during similar dam releases (226 m^3/s vs. fluctuating between 144 and 226 m^3/s). We anticipate that most or part of this accuracy assessment work can be completed in FY14.

In this Project Element, we propose to continue this work by processing an additional 4 sites each fiscal year. In order to successfully process the 1984 photography, we plan to obtain the necessary ground control points for each proposed site. These data will be collected as part of other field efforts described in this project (Project Elements 3.1.1 and 3.2), and potentially as part of other collaborative field work efforts. Thus, this project does not have any stand-alone logistics expenses.

By the end of FY17, we anticipate to have up to half of the long-term monitoring sites processed and analyzed for volumetric change using the October 1984 photographs. Continuing to extend the long-term sandbar monitoring time series back to the early 1980s will provide additional information needed to assess the condition of sandbars prior to ground survey data collection in Glen, Marble and Grand Canyons. The addition of derived topographic surfaces from the 1984 photographs, in conjunction with selected historical surveys will help better inform us on sandbar response to dam operations prior to the 1990s.

Outcomes and Products

- For each completed site:
  - **Spatial Data**: Geodatabase feature class and shapefiles for ground control points and digital terrain model (point cloud), triangular irregular network (TIN) 3D surface derived from point cloud, 25-cm interpolated DEM, and a mosaicked, ortho-rectified image file of 1984 imagery.
  - **Ancillary data**: Photogrammetry block file and triangulation reports, digital terrain model extraction report, vertical and horizontal accuracy assessments of final data sets, volumetric and cross-sectional comparison graphs, and summary reports containing all the above information for each site.
- Report/journal article on long-term trends at the sandbar monitoring sites (joint product with 3.1.1 and 3.2) (*lead author Hazel*).

Project Element 3.2. Bathymetric and Topographic Mapping for Monitoring Long-term Trends in Sediment Storage

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Matt Kaplinski and Joseph Hazel, Research Associates, Northern Arizona University
Bob Tusso, Hydrologist, USGS, GCMRC
Keith Kohl, Surveyor, USGS, GCMRC
Michael Yard, Fishery Biologist, USGS, GCMRC

Objectives

1. Complete the first (baseline) high-resolution bathymetric map of Glen Canyon (RM -15 to RM 0) in 2015.
2. Complete a repeat bathymetric and topographic map of the sediment-budgeting reach from RM 0 to RM 30 in 2016, with a coverage matching that when the reach was first mapped in 2013.
3. Complete the first (baseline) high-resolution bathymetric and topographic map of the long reach from RM 166 to RM 225 in 2017.
4. Implement a recently developed acoustic bed-sediment classification method using Multi Beam Echo Sounder (MBES) data, by factoring in grain size in estimates for changes in sand storage, and in order to better constrain uncertainties in calculated sediment budgets.
5. Report on changes in sand storage in the reach between RM 60 and RM 87, mapped in 2011 and repeat mapped in May 2014.
6. Report on changes in bed elevation in Glen Canyon, based on comparisons between cross-sections last surveyed in 2000 and data from mapping that is scheduled for 2015 (Objective 1).
7. Continue development of methods for classification of bed sediments using MBES backscatter data. In particular, develop means by which to classify bed sediments reliably in the presence of significant coverage of submerged vegetation, such as in Glen Canyon.
8. Develop and implement methods to estimate sand thicknesses below the bed surface, non-intrusively (using acoustics) and which fit into existing channel mapping sampling protocols.

Hypotheses/Questions

1. What are the effect of HFEs and intervening dam operations on sandbar size? (*relates to Section C3, Questions 1 and 4*). We hypothesize that HFEs and intervening dam operations result in a net increase in sandbar size at high elevation (above 8,000 ft^3/s stage) and no net change in sand storage at low elevation (below 8,000 ft^3/s stage)
2. Is the riverbed in Glen Canyon lowering? We hypothesize that the bed of the river in riffles in Glen Canyon remained stable throughout the four HFEs that have occurred since 2000, but pools in Glen Canyon continued to evacuate sediment since 2000. This would imply that the entire riverbed is not lowering. *(relates to Section C.3, Question 4)*
3. What is the spatial distribution of submerged vegetation in Glen Canyon? Can we remotely sense the distribution of submerged aquatic vegetation using MBES backscatter and topography? If so, is it still possible to reliably distinguish between different sediment types (using the recently developed method of Buscombe and others, in review) in the presence of substantial vegetation? *(relates to Section C.3, Question 5).* We hypothesize that it is possible to remotely sense vegetation cover but not to the genus level. We further hypothesize that it is possible to modify the methods of Buscombe and others (in review) to account for the effects of vegetation in classifying sediment types.
4. Is it possible to estimate submerged sand thicknesses using hydroacoustics, reliably and objectively, in order to better quantify absolute sand storage in the parts of the channel which are always submerged? *(relates to Section C.3, Question 4).* We hypothesize that a combination of MBES and chirp sonar would enable acoustic sediment imaging to several tens meters, and that sand thickness estimation would be possible if the acoustic signal is not occluded by layers of coarse substrates.

Rationale/Justification

In this section, we discuss the rationale for conducting comprehensive channel mapping to monitor sediment storage between Glen Canyon Dam and Diamond Creek. Because this project is designed as long-term monitoring, it is necessary to discuss planned monitoring activities in a long-term context, provided below. In summary, we propose to map one channel segment in each of the 3 years of the FY15–17 work plan. These segments are Glen Canyon (RM -15 to 0) in 2015; upper Marble Canyon (RM 0 to 32) in 2016; and west-central Grand Canyon (RM 166 to 225) in 2017. The mapping of the segments in Marble Canyon and Grand Canyon will track long-term trends in sand storage with implications for maintaining and building sandbars in response to HFEs in those segments. As stated above, periodic comprehensive mapping of long reaches is necessary to constrain ΔS within an acceptable level of uncertainty, because flux-based sediment budgets become indeterminate at long (3-10 years) timescales. A repeat map of upper Marble Canyon will be used to evaluate changes in sediment storage in that reach between 2013 and 2016, while also providing an important validation data set for Project 2. The rationales for mapping Glen Canyon and west-central Grand Canyon are somewhat different from the rationale for mapping the other segments and is discussed in separate sections below.

Fine sediment storage

Management objectives for fine sediment have focused on the condition of sandbars. Current management practice includes efforts to maintain and build sandbars using high flow releases that are timed to coincide with periods of fine-sediment supply from tributaries (HFE protocol

EA). As described above in section C.1, the success of this approach is predicated on the maintenance of a sufficient supply of sand within the channel for rebuilding sandbars. The purpose of this sediment storage monitoring element of Project 3 is to track long-term trends in sand storage and thereby provide a robust measure of whether or not the supply of sand available for building sandbars is increasing, decreasing, or remaining stable over time-scales of years to decades. In other words, this project provides the direct measure of ΔS in equation (1) over the time scale of the HFE EA and the LTEMP EIS. Moreover, this project monitors those changes in sand storage by location, providing spatially explicit quantification of the changes in the channel and eddies (ΔS_{low} in equation 2) and sandbars (ΔS_{high} in equation 2).

The greatest challenge in developing an appropriate monitoring program is the scale of the area of management interest, which is the entire CRe from Glen Canyon Dam to Lake Mead. As described above, previous efforts have demonstrated that measurements of sediment storage change made in short reaches cannot be extrapolated to determine sediment storage throughout the CRe. In spring 2012, we repeated the RM 30 to 61 long reach which was first mapped in spring 2009. A spatially explicit analysis of the differences in channel sediment storage once again demonstrated that the large local variability in bed response found almost everywhere necessitates sampling a large proportion of the river channel.

The "long-reach" sampling design used in this project is based on analysis of previous channel bathymetry mapping efforts. Using the repeat maps made of short (< 5 km) reaches between 2000 and 2004, we investigated potential sampling strategies. This was accomplished by artificially subsampling the maps of topographic change that cover an entire 5 km short reach, using three different sampling strategies: (1) regularly spaced channel cross-sections; (2) randomly located channel cross-sections; and, (3) subsampling of major eddy storage locations. This analysis indicated that all of these sampling strategies result in error that is greater than 50 percent of the actual change in storage, unless sampling intervals are sufficiently small such that the level of effort is equivalent to comprehensively mapping approximately 80 percent of the entire reach. Further, the analysis revealed that in order to estimate change in channel storage with an uncertainty of 50 percent of the observed value would require average cross-section spacing of 300 m or less, irrespective of whether the spacing is regular or locations are selected randomly. To achieve a similar level of accuracy by sampling eddy storage locations would require sampling more than 75 percent of those locations. Thus, to reduce the need for, and uncertainties associated with, extrapolation, the monitoring program consists of repeat mapping of most of the bed of the river for long segments.

Although these comprehensive maps of the river bed provide the best measure of changes in sediment storage, mapping long river segments is a significant effort in terms of data collection and data processing. Within the scope of the current budget, it is possible to map and process approximately 30 river miles of channel per year. We have, therefore, developed a proposed schedule for mapping segments in rotation over the next 10 years that is based on the time frames of current and anticipated management actions. Because the segments in Marble Canyon and eastern Grand Canyon (Fig. 3.3) have the greatest risk of sediment deficit and because sandbar response has not been as strong in Marble Canyon as in downstream segments (Fig. 2), channel mapping efforts through 2014 have focused on these segments. The focus will continue to be on these segments for the next 7 years to provide monitoring needed to evaluate the HFE Protocol. By the conclusion of the first 10 years of the HFE protocol in 2021, each of these segments will have been mapped at least 3 times over the 10-year period. This will provide robust and spatially explicit quantification of the change in fine-sediment storage in each segment and a robust measure of the change in all sandbars in each segment. Each of these segments is approximately 30 river miles in length and it is possible to map most of the river bed, excluding rapids and riffles, resulting in maps of 80 to 90 percent of the deposits.

While an exclusive focus on the upstream 3 segments may be appropriate to address the monitoring needs of the HFE protocol, it does not fully address sediment-related AMP goals, which do not distinguish among river segments. There are very few measurements of the channel bed in the segments downstream from RM 87 and there are fewer long-term sandbar monitoring sites between RM 87 and RM 225 (Fig. 6). Without some direct measurements of changes in sediment storage and measurements at a larger set of sandbars than are monitored annually, it will be difficult to assess long-term trends in these segments. We, therefore, propose to collect baseline data within each of these segments within the next 5 years so that repeat maps may be made within the next 10 years. Because these segments are each 60 to 80 river miles in length, we anticipate mapping approximately 50 percent of each segment. Maps of these segments will be less comprehensive than the maps made for Marble Canyon and eastern Grand Canyon and there will be portions of these segments where changes in sediment storage will remain unknown. The maps will, nevertheless, provide a robust quantification of changes in sediment storage for the portions of the segments that are mapped providing much more information than provided by the sandbar monitoring alone.

West-central Grand Canyon

A map of west-central Grand Canyon will provide the first baseline map of a segment downstream from RM 87. Perhaps more fundamentally, the mapping of western Grand Canyon is also the key to making a long-term (decadal to centennial timescale) assessment of the fate of sand canyon-wide. Below we identify a number of major reasons to carry out a one-time mapping effort. First and foremost, establishing a basemap will allow calculations of changing sediment storage decades into the future, well beyond the time-scale of viable calculations of sediment storage changes through sediment flux calculations. Whereas channel mapping provides the information required to assess the impacts of individual and successive HFEs in upstream reaches (Marble Canyon and eastern Grand Canyon), in western Grand Canyon it becomes the means through which the long-term sediment mass-balance can be assessed canyon-wide. The long-term trend in sediment mass balance in the west-central canyon - the sediment monitoring reach furthest from the dam and of greatest contrast with Marble Canyon in terms of sediment size and supply, total sediment storage, extent of riparian vegetation, and hydrology – may be positive, negative, or neutral, and has major implications for system-wide sediment management. Without a basemap of current sand storage conditions of both high and low elevation deposits, future inferences of long-term sediment mass balance in western Grand Canyon will be largely speculative.

The second major motivation for this mapping effort is to collect topographic sandbar data from a large sample of bars, for the purposes of evaluating the annual sampling strategy in this part of the canyon. It is likely that this part of the canyon is greatly undersampled, based on statistical analyses of sandbar sampling in Marble Canyon (Figure 6). Third, baseline mapping of this reach could prove useful for understanding the distribution and abundance of Razorback sucker by, for example, providing maps of the distribution of submerged sediments. Fourth, mapping would also provide geomorphic context to monitoring and understanding riparian vegetation expansion, providing variables such as sandbar grain sizes that are not readily extracted from remote sensing imagery at the required resolution. Finally, application of proposed methodological advances in sub-bottom profiling for the purposes of measuring sand thicknesses could be particularly insightful in this part of the canyon which is hypothesized to have greater total sediment storage than any upstream reach.

Glen Canyon

The needs for long-term monitoring of sediment storage are different in the Glen Canyon segment than in the downstream segments. Because Glen Canyon is upstream from the Paria River, the sediment deficit in this segment is more severe than in the downstream segments (Topping and others, 2003). A series of high flows (pulse flows) released from the dam in 1965 caused rapid degradation of the channel in most of the reach (Randle and Pemberton, 1976; Grams and others, 2007). Grams and others (2007) demonstrated that the pattern of degradation was different for riffles than in pools between riffles. The distinction between pools and riffles is important because degradation of riffles represents incision of the channel – lowering of the entire river bed. In riffles, the magnitude of degradation decreased with distance downstream to the point of zero degradation at the Paria Riffle near Lees Ferry. In addition, the rate of degradation decreased with time causing Grams and others (2007) to hypothesize that this process was complete by 2000, with the possible exception of locations within 1-km of the dam.

In contrast to the riffles, pools more than 20 km downstream from the dam scoured as much or more than pools within 5 km of the dam. Pools continued to exhibit significant changes (scour in some locations, fill in others, with no systematic spatial pattern) in the most recent monitoring interval (1991-2000). Because bed lowering decreases the elevation reached by flows of a given discharge, near the dam the elevation reached by a discharge of 5000 ft^3/s decreased by more than 2 meters between 1956 and 2000 (Grams and others, 2007). Such changes affect many aspects of the aquatic and riparian ecosystems. Scour of sediment from pools, however, is not necessarily associated with channel incision, but instead represents changes in sediment storage. While the channel in Glen Canyon has experienced both incision and changes in storage, segments downstream from Lees Ferry have only experienced changes in storage (Grams and others, 2007).

These changes were documented by repeat topographic/bathymetric surveys of more than 20 monumented cross-sections that were originally established in 1956 for use in designing the dam and power plant. A repeat survey was last made 14 years ago (Grams and others, 2007). The proposed mapping of the channel in 2015 will include a repeat survey of each of those channel-cross sections. Given the legacy of data collection in Glen Canyon spanning several decades, a number of important scientific questions can be addressed using data from a single channel mapping campaign. These surveys will be used to evaluate two hypotheses. First, the measurements will be used to support (or refute) the hypothesis of Grams and others (2007) that the bed is stable in riffles. While it is believed that the channel is stable, continued scour is possible and would have important implications for aquatic habitat (see related biological projects, referenced below). Secondly, the measurements will be used to test the hypothesis of Grams and others (2007) that pools continue to evacuate sediment. These measurements will provide a valuable assessment of the stability of the channel bed and the status of sediment storage in pools early in the implementation of the HFE protocol.

The mapping in Glen Canyon will also provide information required for several aquatic and fisheries related studies. A map of the Glen Canyon segment enables mapping of the relative inundation frequency of trout spawning habitat (see Project 10); establishing flow-habitat relations necessary for studies of egg-laying and emergence behavior of aquatic insects (see Project 5); and parameterizing a model for primary production (see Project 9).

Vegetation and subsurface mapping

In addition to collecting the data to address the questions described above, we also propose work on advancement of methods in two areas. First, we propose to expand our methods for mapping bed composition to include submerged vegetation. It is necessary to be able to distinguish between sediments and submerged aquatic vegetation where coverage of the latter is significant. In addition, given the importance that submerged vegetation serves as habitat for fish and invertebrates (Riis and others, 2008), there is a need to quantitatively examine the spatial distribution, diversity, and abundance of the relatively diverse aquatic plant community found in Glen Canyon. We therefore need a reliable method with which to non-intrusively document the distribution of submerged vegetation with a large spatial coverage. Such a method needs to be able to: (1) remotely sense the water column and bed from a small boat; (2) distinguish vegetation from substrate; and (3) be spatially referenced to enable repeat mapping for the purposes of monitoring. Currently there are no standard methods with which to do this, however, we propose that the use of the MBES in the Glen Canyon channel mapping effort in 2015 is an ideal opportunity to overcome this technological shortfall, for the benefit of the long-term ecological goals of studies of primary production in Glen Canyon, and advancements in acoustic characterization of the composition of riverbeds in general for the purposes of habitat mapping as well as a number of physical goals.

The second advancement we propose involves measuring the thickness, in addition to the surface elevation, of sand on the river bed. We are currently able to report the change in sediment storage (delta S) without knowing the total sediment storage (S) at either time. This has important implications because we therefore do not know how much of S, delta S represents. If delta S is massively negative in a given reach, we do not know how much more sediment would need to be evacuated to completely deplete that reach. Measuring total sediment storage is a daunting challenge because it requires measuring the depth of sediment to bedrock everywhere. However, in recent years seismic frequency acoustic instruments have become more sophisticated and available, opening the possibility of such measurements. Recent advances in bed surface sediment classification means that we can focus sampling efforts over known areas of sandy beds, making the problem of acoustic detection of sand thicknesses much more tractable. Information on sand thicknesses might also be a vital component in designing alternate sampling strategies for capturing the essential components of changes in sediment storage in a given reach. In other words, using sand thicknesses to estimate total sand volumes in a given reach might be critical in determining the return frequency to a given reach. It also provides much needed context for reported changes in sediment storage, by providing the means to begin to answer the question of what the proportion a reported sand storage change is of all sand stored in a given reach.

Methods

It is not logistically feasible to map the entire river corridor in every segment. The goal of this work is, therefore, to map approximately 80 percent of each segment between Glen Canyon dam and RM 87 and approximately 50 percent of each segment between RM 87 and RM 225. Although it is not possible to identify all the important sediment storage locations prior to mapping, the effort is expected to include mapping of more than 90 percent of the large eddy storage locations upstream from RM 87 and at least 75 percent of those storage locations downstream from RM 87. We place greater emphasis on monitoring the three upstream reaches, because the most upstream reaches have greater sediment deficit and are, therefore, a greater risk for long term sand depletion. We further expect that, because these reaches have larger sediment deficit, storage changes are more likely to be spatially variable, requiring monitoring a greater proportion of each mass-balance reach. Each year, one of the five sediment budgeting reaches that are between 26 and 80 miles in length will be mapped such that each segment could be mapped twice in 10 years.

Because about 90 percent of the sand and finer sediment that is available for redistribution by dam operations is submerged (Hazel and others, 2006), the monitoring method must include measurements of the bed of the river in eddies and pools. Data collection will combine multibeam and singlebeam sonars, coupled with conventional topographic surveys for areas above the water surface. These methods have been described by Hazel and others (2008) and Kaplinski and others (2009; 2014) and were used extensively in monitoring the 2008 HFE (Hazel and others, 2010). Similar methods are used to monitor channel changes on other large rivers, including the Missouri River (Jacobson and others, 2009). The data will result in a high resolution digital elevation model of the mapped segments for each mapping effort.

Upon completion of a repeat map of a segment, the maps (DEMs) will be compared to compute the net change in the volume of sediment within the segment. These computations will distinguish between fine and coarse sediment using recently developed acoustic sediment classification algorithms (Buscombe and others, in review), between sediment stored in the channel and eddies, and between sediment at high- and low-elevation. The methods of

Table 3. Long sediment budgeting segments for long-term monitoring of sediment storage.

Segment	River Miles	Completed surveys	Planned surveys	Short reaches*	Cross-sections**	Estimated proportion of reach mapping will cover	Repeat Interval
1	-15 to 0	2000 (cross-sections only)	2015	1	20	80 percent	~ 10 yr
2	0 to 30	2013	2016, 2021	2	41	80 percent	3 to 6 yr
3	30 to 61	2009, 2012	2018, 2023	3	17	80 percent	3 to 6 yr
4	61 to 87	2011, 2014	2020	2	39	80 percent	3 to 6 yr
5	87 to 166	none	2019, 2024	1	20	50 percent	5 to 10yr
6	166 to 225	none	2017, 2022	2	8	50 percent	5 to 10yr

* The number of short reaches 2 to 5 km in length that were mapped at least once between 2000 and 2005 (Kaplinski and others, 2009).

** The number of cross-sections that were measured at least once between 1992 and 1999 (Flynn and Hornewer, 2003).

Buscombe and others (in review) uses MBES backscatter (echo strengths) to distinguish between homogeneous sand, mixed sand and gravel, and homogeneous gravel (Fig. 10). These data are collected in conjunction with soundings used to compute bathymetries; therefore no additional data collection is required. The resulting maps of bed sediment substrates are as highly resolved as the bathymetric maps. Methods for bed-texture classification will continue to be developed in order for us to reliably distinguish between different substrate types (such as the relative proportions of sand and gravel in small areas), in order to assess their relative mobility under a range of flows.

One significant extension to the acoustic sediment classification methods of Buscombe and others (in review) is in being able to distinguish between sediment and submerged vegetation. We propose to use MBES backscatter data, collected as part of the Glen Canyon channel mapping effort in 2015, in conjunction with physical samples and underwater video surveys, to develop and test algorithms with which to reliably distinguish between sediments and vegetation. In so doing, we will have also developed a means by which to make a quantitative assessment of the spatial distribution and areal cover (m^2) of submerged macrophytes, bryophytes, and chlorophytes. Acoustics is, at least in theory, an ideal tool for mapping submerged aquatic vegetation because it is not limited by water clarity or deep water, and provides a much greater coverage, at higher resolution, in a fraction of the time compared with video surveys.

Ongoing analysis between sediment stored in the channel and eddies, and between sediment at high- and low-elevation, will incorporate more sophisticated estimates of uncertainty (e.g. Wheaton and others, 2010; Kaplinski and others, 2014) for which estimates of bed sediment grain size will also be a crucial component. In addition to making comparisons between years for which the entire segments are mapped, comparisons will also be made to earlier data were available (Grams and others, 2013). This will include comparisons to data collected in short reaches in 2000 to 2005, and data collected at monumented channel cross-sections (Table 3).

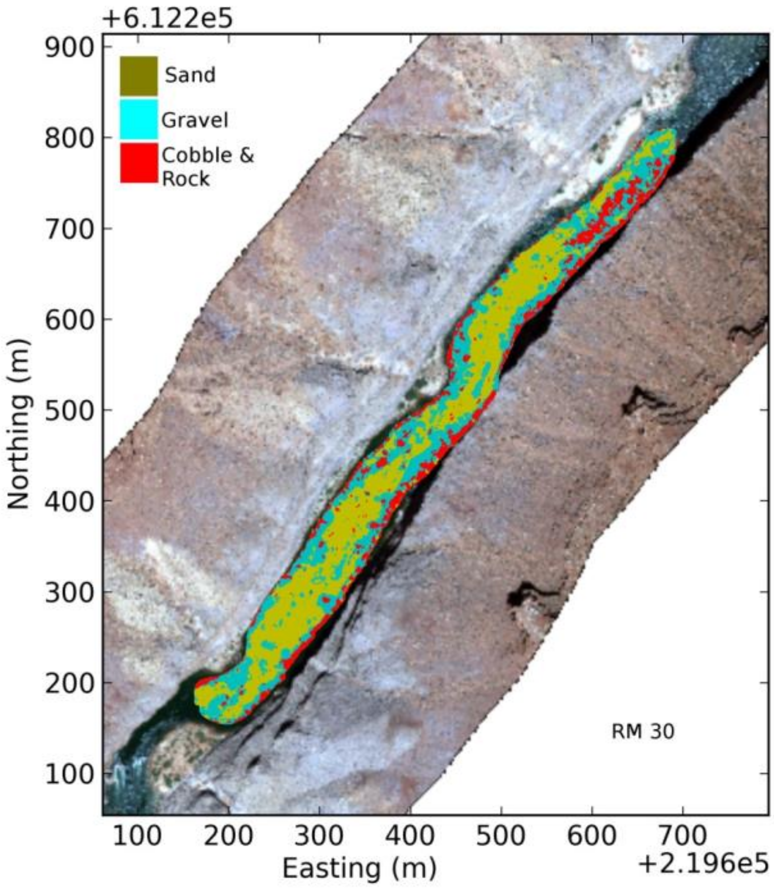

Figure 10. Acoustic sediment classification at RM30, August 2013, using the methods of Buscombe and others (in review). The resolution of classification is 25 cm^2.

In 2016 and 2017 we will evaluate the use of sub-bottom, broadband low frequency (modulated in sweeps ranging from a few hundred Hz to a few kilohertz) acoustic CHIRP profilers to scope the feasibility of determining sand thicknesses below the bed. This would involve testing low-broadband (known as 'seismic') frequency sonars, which penetrate the bed to a much greater depth than the high-frequency sonars (singlebeam and multibeam echosounders) used to map the elevation of the bed surface. The aim is to develop a reliable means with which to estimate sand thicknesses below the bed surface, in order to better quantify the total volume of sand stored in a reach. In recent years, our continuing experience and expertise in the use of sonar mapping techniques has coincided with ongoing technological advances in sonar technology and the increasing use of sonars for estimating the thicknesses of submerged sediment deposits Frequency-modulated (FM, or CHIRP) sonars (Schock and others, 1989) provide higher resolution (a few cm compared with tens of cm) sub-bottom acoustic profiles with less signal noise compared with traditional low-frequency sonars, have been used successfully to image subsurface stratigraphy within sedimentary deposits, typically up to 30m below the surface (e.g. Zeiler and others, 2000; Lafferty and others, 2006). Both the rate of attenuation of the echo strength with depth and the pattern of reflections revealed by concatenating subsequent profiles can be used to discriminate between sediment types. There are several established methods (e.g. LeBlanc and others, 1992; Kim and others, 2002; Schock, 2004; Rakotonarivo and others, 2011). A number of different systems are available for rent. These sonars provide much greater resolution than previous generations of sub-bottom sonars, providing unparalleled detail on the sedimentary sequences down to several tens of meters. We propose to use these systems in areas of known sandy bed surfaces, and develop algorithms to detect sedimentary layers and acoustic attenuations with depth, towards an eventual goal of reliably estimating sand thicknesses.

Relation to Previous Work Plan

The approach in this work plan builds on the project from the FY13/14 work plan. The reaches proposed for mapping in 2013 and 2014 (Table 2) were completed successfully and those data are being processed according to schedule. The major reporting goal for the previous work plan was to report on changes in storage for the reach between RM 30 and RM 61. A preliminary report on this analysis was provided at the January 2014 reporting meeting and the final analysis and reporting is in preparation with submission for review expected by September 2014. A major goal of the previous work plan was the development of automated methods for bed material classification (FY13–14 Project Element A.2.2). This was needed to determine the proportion of the river bed covered by sand and the proportion covered by other substrate, in addition to the utility to other projects for habitat characterization. That project will be successfully completed by the end of 2014 (Buscombe and others, in review) and is therefore not included in this work plan. The methods developed in that project will be used in this project and will continue to be refined and improved upon.

Outcomes and Products – FY15

- Report and maps for RM 0 to 30 (mapped in 2013) (*lead author Kaplinski*).
- Report and maps for eastern Grand Canyon (RM 61 to 87, mapped in 2011 and 2014) (*lead author Kaplinski*).
- Report/journal article on geomorphic changes in eastern Grand Canyon, 2011 to 2014 (*lead author Grams*).
- Report on bed-sediment grain-size measurements using the eyeball system, 2000 – present (*lead author Tusso*).

Outcomes and Products – FY16

- Report and maps for Glen Canyon (scheduled to be mapped in 2015) (*lead author Kaplinski*).
- Report/journal article on geomorphic changes in Glen Canyon, 2000 to 2015 (*lead author Grams*).
- Report/journal article on acoustic detection of submerged aquatic vegetation (*lead author Buscombe*).

Outcomes and Products – FY17

- Presentation at annual reporting meeting.

- Report and maps for upper Marble Canyon (scheduled to be repeat-mapped in 2016) (*lead author Kaplinski*).
- Report/journal article on geomorphic changes in upper Marble Canyon, 2013 to 2016 (*lead author Grams*).
- Report/journal article on long-term trends at the sandbar monitoring sites (joint product with 3.1.1 and 3.1.4) (*lead author Hazel*).
- Report/journal article on the use low frequency sonars to estimate sand thicknesses below the surface (*lead author Buscombe*).

Project Element 3.3. Characterizing, and Predictive Modeling, of Sandbar Response at Local and Reach Scales

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Graduate Student

Objectives

1. Develop groupings of sandbars based on existing measurements of sandbar response and the geometry of fan-eddy complexes. Grouping sandbars that function similarly will allow us to use these groupings to model generalized eddy hydraulics and morphodynamics (two-way feedbacks between morphology and flow) as part of Objective 2 and document statistically the physical factors most important to different sandbar behaviors for the empirical parametric model in Objective 3.
2. Continue the development and testing of a 3-dimensional large-eddy simulation (LES) model for coupled streamflow, sediment transport, and sandbar morphodynamics in eddies, and link the numerical LES modeling of eddies with large-scale statistical characterization of eddies.
3. Develop a statistical model that links channel geometry with flow (driven by simple, measurable physical parameters) and predicts average behavior of individual, or groupings of, sandbars.

Hypotheses/Questions

1. What are the typical sandbar morphologies associated with specific fan, channel, and eddy geometries? Can we develop groupings of bars from a synthesis of existing data sets on sandbar form and dynamics? We hypothesize that different fan-channel-eddy geometries are a primary driver of the observed differences in sandbar behavior in response to different flows (section C.3., question 3).
2. Are differences in sandbar response driven by the topographic boundary conditions of a given reach, or more strongly linked to flow and sediment supply boundary conditions? We hypothesize that topography is at least as important as sediment concentration in sandbar response to different flows. We will use a topographically flexible form of the 3-dimensional LES model to assess the dominant controls among sites (section C.3., question 3).

3. How can we parameterize metrics of sandbar size and change statistically or semi-mechanistically to serve as the basis for a predictive model for average or aggregate sandbar responses to future flows? Can we predict the response of individual bars, or groupings of bars that behave similarly, using a comparable modeling approach? We hypothesize that statistical approaches can be used to model sandbar response to different flow scenarios with increasing sophistication given results from objectives 1 and 2 (section C.3., questions 2 and 3).

Rationale/Justification

Characterizing and predicting sandbar response to varying flow and sediment inputs over long reaches or at individual sites, based on mechanistic or empirical models, has long been a desired research and management goal. Continued advances in computational efficiency combined with long-term data on sandbar and channel morphology collected as part of the monitoring program, allows us to advance our understanding of eddy sandbar dynamics beyond what has previously been achieved. The long-term monitoring data includes more than two decades of sandbar measurements (Project Element 3.1.1), topographic measurements of the full river channel for long reaches (Project Element 3.2), measurements of sandbar grain size (Project Element 3.2), remote camera images (Project Element 3.1.1), remotely-sensed data of sandbar distributions throughout the CRe (Project Element 3.1.2), and more than a decade of sediment flux monitoring (Project 2).The work proposed in this project element is motivated by several observations: (a) both immediate sandbar response to HFEs, and longer-term response to intervening dam operations, differ among eddies, sometimes over very short distances where discharge and sediment supply conditions are likely similar; (b) this difference in sandbar response must result from spatial differences in the coupled hydraulic and sediment transport processes that result in differing rates of erosion of, and/or deposition on, sandbars during different discharges and sediment supply conditions; and (c) understanding differences in sandbar responses may be made more tractable by generalizing responses into groupings of bars based on fan, channel, and eddy geometries. The latter of these provides a basis for understanding how much a change in river geometry influences sandbar depositional and erosional processes. In this proposal, we approach this problem spatially by comparing measured sandbar response to the characteristics of different fan-eddy complexes throughout the river corridor.

Sandbars in Marble and Grand Canyon are formed primarily in zones of recirculating current (eddies) downstream from channel constrictions created by debris fans at the mouths of tributary drainages (Howard and Dolan, 1981; Schmidt, 1990; Schmidt and Graf; 1990; Melis, 1997). The interaction between stream flow and channel topography is the dominant control on flow hydraulics in rivers, and, in turn, the interaction of flow hydraulics with the bed sediment causes sediment transport and patterns of erosion and deposition. Thus, the location of, and morphodynamic changes to, eddy sandbars is strongly dictated by interactions of the river's flow with coarse-grained debris fan deposits. There is a wide range in eddy sandbar response to different dam operations and to floods (Schmidt and Graf, 1990; Beus and others, 1992; Hazel and others, 1999; Hazel and others, 2010; Schmidt and Grams, 2011). This variability may reflect sampling design, differences in reach-scale sand supply, or a difference in hydraulic characteristics among eddies. Recently, Grams and others (2013) showed that local variability in sediment storage in short (2.7 – 4.7 km long) reaches is at least as large as the variability between reaches in Marble Canyon. They conclude that, because sediment supply conditions are likely not changing appreciably over short reaches, local flow hydraulics are the dominant factor causing differences in response. For example at some sites, sand storage increases with discharge, and at others sand storage decreases with discharge (Fig. 11). There is no downstream trend favoring one type of site behavior, and sites very near each other may show the opposite correlation with discharge (Fig. 11).

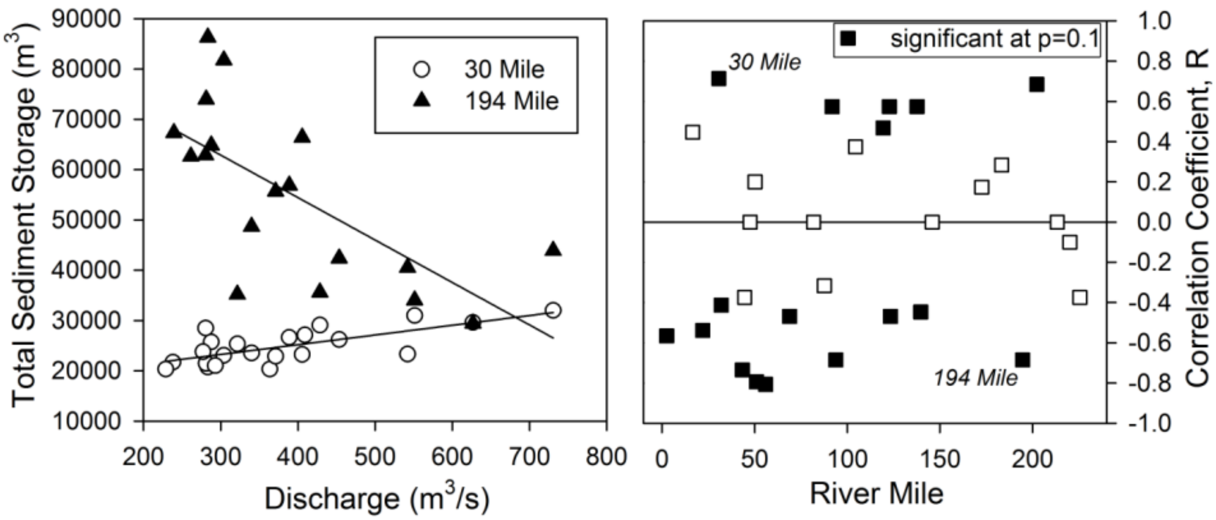

Figure 11. Left) Changes in observed total sand storage as a function of recent discharge for two of the long-term monitoring sites. Right) Downstream trends in the correlation coefficient, R, of the discharge-sediment storage relations. Positive (negative) values indicate increases (decreases) in sediment storage with discharge; closed (open) squares are locations where the regression is (is not) significant.

The work of Grams and others (2013) and the results shown in Figure 11 suggest that local differences in flow hydraulics are likely to be a dominant factor influencing how site-scale fine sediment storage changes in response to changing discharge conditions, but do not link these differences among sites directly to feedbacks between fan-eddy geometry and channel hydraulics. Thus, the purpose of Objective 1 is to link the observed measurements of sandbar change to topographic, hydraulic, or geomorphic metrics of the larger fan-eddy complexes, which then can be used to develop groupings of eddy sandbars that are functionally similar. Previous researchers have described several metrics of fan, channel, and eddy characteristics (e.g. Schmidt, 1990; Schmidt and Graf, 1990; Melis, 1997; Hazel and others, 2010). For the channel, these include the constriction ratio, expansion ratio, recirculation zone length, constriction length or total length of the rapid, eddy size, stage change with discharge, divergence angle or jet angle (Fig. 12), water surface slope, and changes in depth between the constriction and expansion. Several other metrics describe the geometry of the fans impinging on the channel, including fan spacing, fan shape, and fan height (Schmidt and Graf, 1990; Melis and others, 1995; Melis, 1997). The size and occurrence of sandbars is also related to changes in canyon width caused by changes in river-level bedrock (Schmidt and Graf, 1990). These changes in canyon width often co-occur with changes in the characteristics and distribution of debris fans impinging the flow of the river (Melis, 1997), and provide a framework for aggregating individual site scale data (Schmidt and Grams, 2011). Preliminary results (P. Grams, unpublished data) show that there is no simple correlation between measured changes in sandbar volume and many of these parameters. Because previous attempts at grouping sandbar response have not worked adequately, more robust statistical methods or new metrics are needed to define possible empirical relationships that can be linked to river processes.

Metrics of fan, channel, and eddy geometry or other hydrologic parameters that relate to changes in sandbar size provide proxies for changes in flow hydraulics and sediment transport processes in fan-eddy complexes. In Objective 2, we propose to link differences in topographic boundary conditions to sandbar response using a large eddy simulation (LES) model; LES is a mathematical technique that allows large-scale turbulence to be directly computed in numerical hydrodynamic models. Work currently in progress (FY13–14 Project Element A.3) includes development of a new 3-dimensional LES model for flow and sediment transport in eddies of the Colorado River. The hydraulic (streamflow) component of the model has been validated (Alvarez and others, 2013; Alvarez and others, *in prep.*). More recently, components that allow for computation of sediment transport and bed morphodynamics have been added to the model. The LES approach has revealed the importance of using both a three-dimensional and time-dependent model in lateral separation eddies. The model shows that the difference in direction of surface and near-bed flow vectors and low-frequency variation of the strength of the eddy recirculation current are key features necessary to model the import and export of sediment from sandbars. Work is in progress to use the validated flow model in a topographically-flexible form to evaluate the effect of differences in channel geometry on temporal and spatial patterns of sandbar deposition and erosion. From our empirical analysis relating sandbar form and change to fan-channel-eddy geometry (Objective 1), we intend to develop groupings of sites that can be modeled using the flexible form of the LES model. The LES modeling will therefore elucidate the flow hydraulics and sediment transport processes important to different sandbar behaviors.

The last goal of this project is to develop a more generalized predictive model for average or aggregate sandbar responses to future flows (Objective 3). This is a challenging goal for a river corridor as long and varied as the Grand Canyon, thus progress is incremental, but would be of great use for resource management. Previous efforts to model individual or aggregate sandbar response have had mixed success. Models for streamflow and sediment transport for individual eddies have been used to successfully evaluate the rate of sandbar deposition during high flows (Wiele and others, 1999) or following tributary inputs (Wiele and others, 1996). More recently, Wiele and others (2007) constructed a reach-averaged model for streamflow, sediment transport, and sandbar response. This model used 1-dimensional flow and sediment transport relations to predict downstream changes in sediment mass balance to drive sandbar erosion and deposition. The processes of sandbar erosion and deposition were based on empirical relations with flow and eddy properties derived from 2-dimensional model outputs from a subset of eddies. The model results generally agreed with measurements of sand flux and suspended sediment grain size, but consistently under-predicted the magnitudes of sandbar response, evaluated against that measured at the long-term monitoring sites. An advantage of the approach used in the Wiele and others (2007) model is that it is physically based. A disadvantage is that it does not provide a means to predict the response of individual bars or groupings of bars that may be of interest to managers. Another modeling approach was developed for the analyses of the LTEMP EIS alternatives that is highly empirical and is parameterized with the observed sandbar volume data. This approach matches the overall trend in the sandbar volume data series, but suffers from a parameterization whose physical meaning is unclear, and seeks to model all sandbars as a single representative sandbar for all of Marble Canyon.

While the approaches above address the problem from different perspectives, neither approach allows for a prediction of the behavior of individual bars, nor groupings of similar bars, to different flow and sediment supply scenarios. This simplification has been made because (1) we lacked the information necessary to address variability among the many different sandbars and, (2) we lacked a reasonable means to extend modeling efforts to the many sandbars for which no monitoring information was available. For example, Wiele and others (2007) used data through 2004 in their model, and the availability of many new data sets in the subsequent decade will allow us to develop a more data-driven model of sandbar response for either individual bars, or groupings of similar bars. These data sets include suspended sediment monitoring (http://www.gcmrc.gov/discharge_qw_sediment/), the Wright and others (2010) shifting rating curve model of sand transport, bathymetric surveys of the channel bed (Kaplinski and others, 2014), surveys of sandbar volumes (Hazel and others, 2008), an extensive time series of remote camera images of sandbar change (http://www.gcmrc.gov/gis/sandbartour2013/index.html), and remotely sensed data from the entire CRe (Project Element 3.1.2). Furthermore, results from our empirical analysis of sandbar groupings and from the three-dimension LES modeling will allow for a more robust characterization of the functional form of process-response relationships important to sandbar deposition and erosion. For example, can we use the long-term sandbar surveys to develop robust relationships between sandbar volume and area, which could be used to extend modeling efforts to sandbars that have only been characterized with aerial photos? Can we improve functional relations between discharge or eddy characteristics and magnitudes of sandbar erosion and deposition, building on the work of Wiele and others (1999, 2007)?

While a collection of sites have been monitored for almost 25 years, these represent only a very limited subset of all sandbars which may not be representative of the dynamics of all bars (hence Project Elements 3.1.2 and 3.1.3). Thus, if a parametric (data-driven) model is based on the data from, but is designed to apply to more than these few sites, it must include some provision for extrapolating to a larger number of sandbars without being overly sensitive to the specifics of any given bar. What limits an *ad hoc* approach to this scaling is the diversity in sandbar responses to the same flow and sediment conditions, owing to complex relationships among sandbar morphology and streamflow, suspended sediment concentration, bed sediment grain size, fixed channel geometry, and existing sandbar morphology. Objective 2 allows us to address these different factors mechanistically using the LES model, while Objectives 1 and 3 will allow us to develop more sophisticated approaches using our growing body of information to build a more generalized statistical or semi-mechanistic model of sandbar response to high flows and intervening flows over event- to decadal-timescales, building on the work of previous scientists. Objective 3 will include collaboration with Bureau of Reclamation staff that developed the empirical model for the LTEMP EIS.

Methods

Objective 1:

In the first phase of our analysis, we will identify groupings of sandbars based on morphological properties and temporal response to different flow regimes using the long-term sandbar data set. As a first step, we will group those sandbars that exhibit similar discharge-to-sandbar-volume relationships (Fig. 11); for example, those sites that show positive, neutral, or negative relationships would form the initial groupings. We will also use a statistical clustering (dimensionality reduction) approach on sandbar metrics such as volume, area, thickness, slope, planform shape metrics, concavity, and grain size, and/or the persistence and time-derivatives of these quantities to determine whether these metrics allow for additional groupings (or clusters) of bars. Once we have established different bar groupings, we will use a statistical Analysis of Variance (AnoVa) technique to determine which hydrologic or geomorphic metrics separate the groups. Many of these metrics (listed above) have already been determined for many of the fan-eddy complexes that are part of the long-term sandbar data set (e.g. Schmidt and Graf, 1990; Hazel and others, 2010), and we will formalize a database with these metrics for each sandbar site. This will include defining these metrics where they do not exist, and developing new metrics for each site. Previous researchers had only limited data on the topographic form of the submerged portion of the channel bed, which must be an important control on flow hydraulics in the eddy recirculation zone, and is a primary input into the LES model of Objective 2. Thus, new metrics will include those developed from detailed measurements of the full river channel topography over long reaches collected over the last decade and continuing in Project Element 3.2. For example, we can define metrics of topographic relief between pools and adjacent recirculation eddies (Fig. 3.12a). Once we have a complete database of sandbar and fan-channel-eddy metrics, we can analyze the data set systematically for statistically significant relationships.

For sites where the full reach channel mapping has been repeated, such as lower Marble Canyon, we can assess whether the groupings developed from the long-term NAU sandbar monitoring sites are appropriate for aggregating sandbar behavior in longer reaches. In addition, Project Element 3.1.2 will provide a comprehensive “large eddy dataset” of sand area and volume in 2002, 2009, and 2013 for 1300 eddies throughout the river corridor using remote sensing; a base map of geomorphic deposit types, including debris fans, eddies, and sandbars, will also be created. These data will initially be used to assess the representativeness of the NAU sandbar sites, in terms of sandbar area and volume or changes in these quantities, for different geomorphic reaches throughout the river corridor. Depending on the outcome of the sandbar grouping analysis at the NAU sites, these data may also be used to extrapolate or validate these groupings for long reaches based on fan, channel, or eddy characteristics and corresponding sandbar characteristics.

The outcome of this objective will feed into the next objective, which is to investigate the generalized flow hydraulics and sediment transport processes associated with the different groupings of eddy sandbar types. We will relate differences in measured channel geometry among sites to the identified sandbar groupings. We will then incorporate several generic channel geometries into the LES model that are representative of the major sandbar groupings. This will allow us to link the topographic boundary conditions (as determined by channel geometry) to processes of erosion and deposition in eddies, and compare these results to the observed changes in sandbar size and shape. Together, the results from Objectives 1 and 2 will provide insight into the important physical processes and their functional forms for incorporation into Objective 3.

Objective 2:

The goal of this effort is a physically-based numerical model capable of predicting sandbar size (area and volume) and morphology (shape) given routinely measured or modeled streamflow characteristics, suspended sediment supply, and sandbar configuration. Because of the temporal and/or spatial resolution of the required inputs and high computational demands of this model, it is not expected to be a suitable operational model for all sandbars in Grand Canyon. Rather, it will be a tool to help understand the interactions amongst the suite of driving variables and processes of sandbar response at selected sites, and will allow ranking of these variables and processes by their relative importance. In order to generalize the model to characteristic sites, we will use the data compilation and analysis in Objective 1. This information will then be used to refine a more generalized empirical or statistical model for sandbar response applicable to all sandbars in Grand Canyon (Objective 3).

Large Eddy Simulation (LES) is a computationally intensive modeling technique in which turbulence larger than the scale of the grid is directly calculated by the equations of fluid motion. Current parallel algorithms employed on supercomputers are now able to perform simulations of turbulence and suspended sediment transport on grid spacing of a meter or less when applied to Grand Canyon fan-eddy complexes (Alvarez and Schmeeckle, 2013). The LES model developed for Grand Canyon eddies simultaneously solves for the turbulent flow field and the suspended sediment concentration field by solving the three-dimensional, time-dependent sediment concentration continuity equation. The flow and suspended sediment has very recently been coupled with a morphodynamic model based on the rate of erosion or deposition predicted by the model. The morphodynamic model also utilizes a bed mixing depth model to evolve the grain sizes available for transport from the bed.

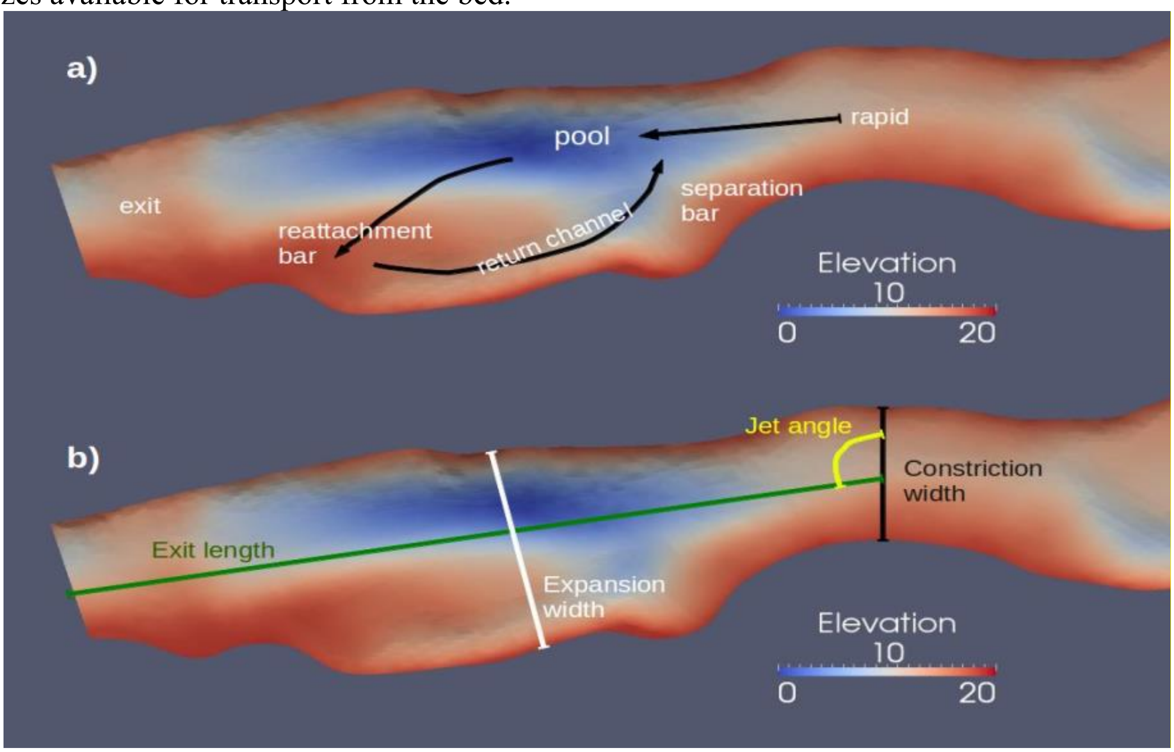

Figure 12. a) General topography of an eddy and b) geometric parameters influencing flow hydraulics.

Figure 12a shows general topographic features of a lateral recirculation eddy. Figure 12b shows a subset of possible geometric parameters that may be found to be important in the groupings determined by Objective 1. A generic grid will be formed and the geometric parameters of each bar group from Objective 1 will be used to form a synthetic grid that corresponds to each bar group. The LES flow and suspended sediment model will be conducted on each bar group synthetic grid. We will focus attention on the key flow features for import and export of sediment from the lateral eddy zone to test our Hypothesis/Question 2 that different sandbar responses to similar sediment and water discharges are the result of specific topographic boundary conditions.

Objective 3:

We will use existing field and remotely sensed data sets, which include coupled (concurrent and co-located) observations of sandbar response and hydrology, to develop a data-driven model of sandbar response to HFEs and other flow regimes. This model will predict the generalized response of a given sandbar (sandbar volume and/or area) and/or groups of similar bars (Objective 1) given inputs of routinely measured or modeled flow and sediment parameters, and measured or modeled (depending on availability at a given model time step) sandbar parameters. The model will be empirical (as opposed to the mechanistic model of Objective 2), and calibrated and validated with existing long-term sandbar monitoring data. The applicability of the model beyond the monitoring data on which it is built will be evaluated using data from the channel mapping projects (Project Element 3.2.), the remote sensing of sandbars (Project Element 3.1.2.), the remote camera element of the sandbar monitoring program (Project Element 3.1.1), and the rapid survey project (3.1.3).

Our modeling approach is to begin simply, and incorporate complexity as results from Objectives 1 and 2 allow us to refine our understanding of the key physical processes. First, we will use an empirical statistical approach to model sandbar response for individual bars and for groupings of bars (Objective 1). This work will proceed concurrently with Objective 1 in collaboration with David Varyu of the BOR, who developed a generalized empirical model for the average behavior of all sandbars in Marble Canyon for the LTEMP EIS. Our initial approach will use a simple parametric model of individual or grouped sandbar response. Examples include a multiple regression approach, a mixed-effects model, or a model based on statistical unsupervised learning methods that is trained on the existing data set. The latter approach finds parameters based on statistical principles such as minimizing variance, but which have defensible physical meaning. Using results from Objectives 1 and 2, we will attempt to develop a more sophisticated statistical model that is based on calibrated physical parameters derived from physical principles and understanding and empirically-derived response rates. This approach could include re-application of the Wiele and others (2007) approach using the new data sets collected in the last decade if practicable in light of results from the preceding approaches. For example, we can develop empirical relations between (1) eddy properties and rates of sandbar erosion or deposition for different discharge conditions (e.g. Wiele and others, 2007), (2) between sandbar volume or mass balance (erosion or deposition) and flow/sediment transport parameters (e.g. Fig. 11), or (3) between sandbar mass balance and the morphological characteristics of those bars in deficit, and those in surplus, over specific periods.

For Objectives 1 and 3, we intend to focus initially on lower Marble Canyon, where there is a higher density of long-term monitoring sandbar sites, repeat bathymetric surveys from channel mapping campaigns in 2009 and 2012, and a complete geomorphic base map of channel characteristics and geomorphic units (P.E. Grams, unpublished data). We will then test the applicability of applying the data-driven empirical model to upper Marble Canyon and different segments of Grand Canyon. Field surveys in reaches outside of lower Marble Canyon, combined with Canyon-wide remote sensing data, will allow us to document the longitudinal occurrence of different eddy sandbar types, and provide a validation data set to test applicability of the model. We also expect that the spatially rich, remotely-sensed data will be important for providing insight into improving the approach described here for longer reaches or in other segments of the CRe.

Outcomes and Products – FY15

- Development of the sandbar groupings and database of fan-channel-eddy metrics (Objective 1)
- Development and implementation of "flexible" version of LES model compared with measured sandbar response in different sandbar groupings (Objectives 1 and 2)

Outcomes and Products – FY16

- Presentation at annual reporting meeting on results of linking the generalized sandbar groupings (Objective 1) with the topographically-flexible LES model (Objective 2)
- Develop a simple statistical, parametric model of sandbar response to HFEs and intervening flows (Objective 3)
- Report/journal article on generalized sandbar groupings from morphological characteristics of the channel and bars and/or results from the "flexible" LES model (*lead author Mueller*)

Outcomes and Products – FY17

- Presentation at annual reporting meeting integrating the statistical and LES modeling approaches to understand spatial and temporal variations in sandbar dynamics
- Continue refining the parametric model (Objective 3), with the potential for developing a semi-mechanistic model incorporating results from Objectives 1 and 2
- Report/journal article on statistical sandbar model to predict sandbar response using the monitoring data set (*lead author Mueller*)
- Report/journal article on coupled flow and morphodynamic LES model of Grand Canyon sandbars (*lead author Schmeeckle*)

Project Element 3.4. Connecting total sand transport, bed morphodynamics, and sand budgets in Grand Canyon

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Daniel Buscombe, Research Geologist, USGS, GCMRC
Paul Grams, Research Hydrologist, USGS, GCMRC
David Rubin, Professor, University of California at Santa Cruz
David Topping, Research Hydrologist, USGS, GCMRC
Graduate Student

Objectives

1. Carry out repeat high-resolution bathymetric and flow-field surveys over sand bedform fields in select reaches, over a range of discharges, including a controlled flood (Wright and Kaplinski, 2011) and flows associated with routine dam operations.
2. Use these data to estimate bedload and bed sand fluxes associated with the deformation and migration of bedforms by applying, and modifying where necessary, existing numerical techniques and theory.
3. Determine a bedload 'rating curve' which relates sand flux as bedload with routinely measured flow and sediment quantities (discharge, or suspended sand flux, or both).
4. Use the rating curve in conjunction with a discharge model to estimate a total bed-material sand mass balance for Marble Canyon and eastern Grand Canyon (stations at

RM 30, RM 61, and RM 87), combining estimates of sand bedload flux with sand suspended flux to enable estimation of total sand transport, system-wide and nearly continuous in time.

5. Develop a conceptual 'bed state indicator' model relating bedforms in a given reach classified by their morphology and sedimentology to the surplus or otherwise of sand in the bed, and therefore the propensity of the bed in that reach to contribute sand for sandbar building during controlled floods.
6. Examine the two-way feedbacks between evolving bedform fields and spatial distributions of flow and sediment concentrations, in order to better understand the potential time-varying importance of bedload sand flux. This is necessary to estimate the representativeness of suspended sediment measurements for bed sand flux estimates at discrete locations.

Questions / Hypotheses

1. What is the contribution of bedload to time-integrated sand flux in the Colorado River in Grand Canyon? How does this vary with discharge, suspended sand load, hydraulic geometry, and bed sediment grain size? We hypothesize that the fraction of sand moving as bedload varies inversely with discharge above the suspension threshold (e.g. Maddock, 1976), positively with bend radius and channel width, and positively with grain size. *(relates to Section C.3, Question 6)*
2. Does bedload flux scale with suspended sand flux? We hypothesize that (1) bedload sand flux varies non-linearly with suspended sand flux, because the presence of bedforms enhances local sediment suspension by adding form drag to total bed shear stress (Einstein, 1950); and (2) the importance of incorrectly estimating bedload sand flux increases at low discharges and transport stages. *(relates to Section C.3, Question 6)*
3. Can reach-scale estimates of sand flux and sediment mass balance improve with direct quantification of the contribution of bedload transport, using routinely measured quantities at gaging sites (discharge, suspended sediment concentration and grain size)? We hypothesize that more robust parameterization of bedload flux will enable partial if not complete accounting for discrepancies between morphologic and suspended sediment based estimates of sand mass balance. *(relates to Section C.3, Question 6)*
4. Can geometric and sedimentologic characters of bedforms be used as a 'bed state' indicator? What bedforms (if any) indicate sediment-starved beds, and what (if any) represent significant stores of sand that could be re-mobilized during controlled floods to build sandbars? We hypothesize that certain bedform shapes and grain sizes are indicative of thin veneers of sand, and others indicate thick sand bed deposits. The use of bedform classification (geometric characteristics and sedimentology) is common in field and experimental settings to indicate the presence or otherwise of a starved sand bed. For example, the existence of 'sand stripes' indicate relatively starved bed conditions (Grams and Wilcock, 2007), as do dunes with coarse underlying sediment exposed in the troughs. High amplitude dunes with more regular geometries indicate areas with a surplus of sand-sized sediment. *(relates to Section C.3, Questions 4 and 6)*

5. Do evolving bedform fields alter hydraulic conditions and suspended sediment concentrations? We hypothesize that, for a given flow field and upstream suspended sediment supply, an evolving bedform field alters the spatial distribution of total bed shear stress sufficiently, through form drag, to alter the concentration and spatial distribution of suspended sand. This is manifest as non-equilibrium responses in the distribution of sand flux between bedload suspended load, calculated using Einstein's (1950) shear stress partitioning method with skin frictions estimated from known grain sizes. *(relates to Section C.3, Question 6)*

Rationale/Justification

By measuring and parameterizing bedload sand flux (the rate of flow of the mass of sediment per unit area), this project will contribute to the sediment monitoring program as an important component of both flux-based and morphologic-based estimates of sand mass balance in Marble and Grand Canyons (Grams and others, 2013). This project has the potential to substantially improve estimates of mobile sand volumes that are available for sandbar construction during controlled floods within a specific reach.

The method with the highest potential for spatially explicit estimates of bedload sand flux over large areas (100s to 1000s of square meters) is through the time-evolution of bed topography in entire pools (up to 1 km in length) captured at a time scale of hours to days. From the pioneering work of Bagnold (1941) and Simons and others (1965), fluxes of bed sediment have been directly tied to the migration of idealized triangular mobile bedforms. These early techniques have been modified to suit application in large rivers (e.g. Mississippi River, Nittrouer and others, 2008; Missouri River, Gaueman and Jacobson, 2007, and Abraham and others, 2010) where bedforms are not idealized shapes, and where bedforms deform as they migrate. McElroy and Morhig (2009) proposed an extension to these methods that captures all bed-sediment flux through analyzing the evolution of sand bedforms. This relatively new method has not yet been systematically tested on numerous river systems, but there is some support for it with existing data (McElroy and Abraham, 2010). The sediment monitoring and channel mapping programs combine to provide a unique opportunity to carry out a robust test of existing methods, by coupling spatially explicit measurements of bedform evolution with detailed measurements of suspended bed sand fluxes. We propose to capitalize on the following recent advances to connect suspended sand fluxes to bedload sand fluxes and, in combination, the sand budget in Grand Canyon.

First, it is now possible to measure bathymetry using MBES with extremely high resolution (cm), high accuracy (cm), and high precision (cm). Second, recent advances have been made in estimating bed-sediment surface grain-size using MBES acoustic backscatter. Third, it is now possible to measure and record the acoustic scattering signature of sediments suspended in the water while mapping bathymetry (Hughes-Clarke, 2006), opening up the possibility of quantifying spatial heterogeneity in suspended sediment concentrations (Jones, 2003; Simmons and others, 2010). We are therefore close to being able to measure bathymetry, bed sediment grain size and suspended sediment concentration simultaneously with the same instrument, and with no additional field time. These advances will be applied to estimating bedload and bed load sand flux using repeat surveys over bedform fields.

We know that not all sand in the Colorado River moves through Grand Canyon in suspension; some near-bed transport occurs below the detection of acoustic suspended sediment samplers. Current acoustic sediment monitoring (Project 2) captures the suspended sand flux but not the flux of sand that moves as bedload. Instead, bedload sand flux is estimated as the same constant proportion of suspended sand flux at each gage station (Topping and others, 2010). The percentage used (typically 5 percent; Fig. 13a) is an estimate based on limited field observations. This practice is based on a study by Rubin and others (2001) who used measurements of bedform wavelength made by rotating side-scan sonar in eddies, estimates of bedform height, and point measurements of suspended sediment concentration to estimate that bedload was approximately 5 percent and 0.3 percent of total sand flux at the 61-mile and Grand Canyon gages, respectively. This represents two point measurements over a 20-m circular section of channel bottom over 10-20 hours during a discharge of about 20,000 ft^3/s.

Based on those data, there are substantial uncertainties surrounding the present use of a constant proportion of suspended sand flux as an estimate for bedload flux. For example, what are the spatial variabilities of bedload flux? How do the controls and rates of bedload differ between the main channel (not measured by Rubin and others, 2001) and eddies, which are fundamentally different flow regimes? Is bedload flux always in phase with discharge and/or suspended flux, or is there some time-lag or hysteresis effect in place due to the deformation and/or migration of bedforms? What are the feedbacks between evolving bedform fields, and fields of flow velocity and suspended sediment concentrations? What is the effect of bed sediment grain size distribution on bedform movement and therefore bedload flux? Bedload sand flux is not likely to be larger than ~10 percent of the suspended sand flux. However, variations between ~1 percent and ~10 percent of the suspended flux are possible, both temporally and between gages. These variations could significantly affect computed sand budgets. For example, if bedload sand flux is ~1 percent at one station and ~10 percent at another station, this adds ~10 percent possible bias to the sand budget for the intervening river segment if bedload fluxes are erroneously assumed to be equal at both stations. Using the sediment budget tool on the GCMRC website (Lower Marble Canyon, May 2009 to May 2012) this could mean the difference of a budget that is -800,000 metric tons with uncertainty range of -1,100,000 to -490,000 metric tons to a budget that is -800,000 metric tons with uncertainty range of -1,700,000 to +100,000 metric tons. The 10 percent potential bias in the bedload flux adds substantially to the uncertainty in the estimated sand budget. Thus, until we have a better understanding of these processes, the application of a universal linear relationship between suspended and bedload sand fluxes (Fig. 13a) will continue to add potentially substantial uncertainties to total sand fluxes in Grand Canyon. We hypothesize that the proportion of total sand load moving as bedload varies with flow strength (discharge; Fig. 13b).

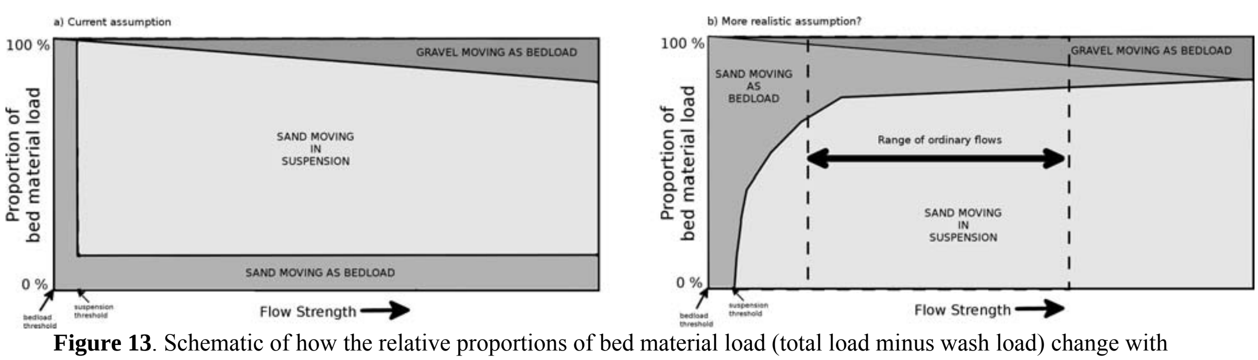

Figure 13. Schematic of how the relative proportions of bed material load (total load minus wash load) change with increasing flow strength. Two scenarios are presented: (a) represents the current assumption that bedload is a constant proportion of bed material load; and (b) depicts the new hypothesis to be tested in this study that the proportion of bed material load moving as bedload is a function of flow strength.

One of the goals that we propose is to significantly expand the dataset on which the conclusions of Rubin and others (2001) are based. Primarily this includes: (1) measuring bedform geometry (wavelengths and heights) more accurately (using MBES rather than sidescan sonar), over a larger area, and in both the main channel and eddies; (2) observing the evolution of that geometry over a greater range of flow conditions and at sites which are specifically tied into the existing suspended sediment monitoring program; (3) measuring the surface grain size of sand comprising the bedforms; and (4) using recent theoretical understanding and computational advances in estimating bedload flux from high-resolution bathymetries (McElroy and Mohrig, 2009).

We will integrate our field measurements with ongoing work to maximize the utility of the project. Primary connections will be made with two other projects, namely (1) suspended sediment monitoring, and (2) acoustic bed sediment classification. Underwater video has revealed the existence of gravel troughs between sand bedforms, as well as small dunes in mixed sand-gravel substrates. In addition, there is anecdotal evidence dunes composed entirely of gravel exist on the bed of the Colorado River in Grand Canyon. Using MBES acoustic backscatter, Buscombe and others (in review) have developed methods which will allow us to distinguish bedforms between different substrate types (homogeneous sand, mixed sand and gravel, and homogeneous gravel).

Methods

This study will be achieved primarily using repeat MBES and ADCP surveys. The MBES will provide bathymetric maps, as well as maps of surface bed sediment type at the same resolution, and full water column backscatter measurements for visualizing the 3D suspended sediment field. The ADCP will provide measurements of flow velocity fields. Repeat mapping of the riverbed using MBES has been shown to be able to capture the migration and deformation of sand dunes over short time scales (hours to days) during a controlled flood (Wright and Kaplinski, 2011; also Fig. 14). The MBES system currently in use allows better resolution of the bed morphology, therefore a smaller threshold of change detection. We anticipate that capturing the same degree of mobility under regular flows from normal dam operations would take several days to a week.

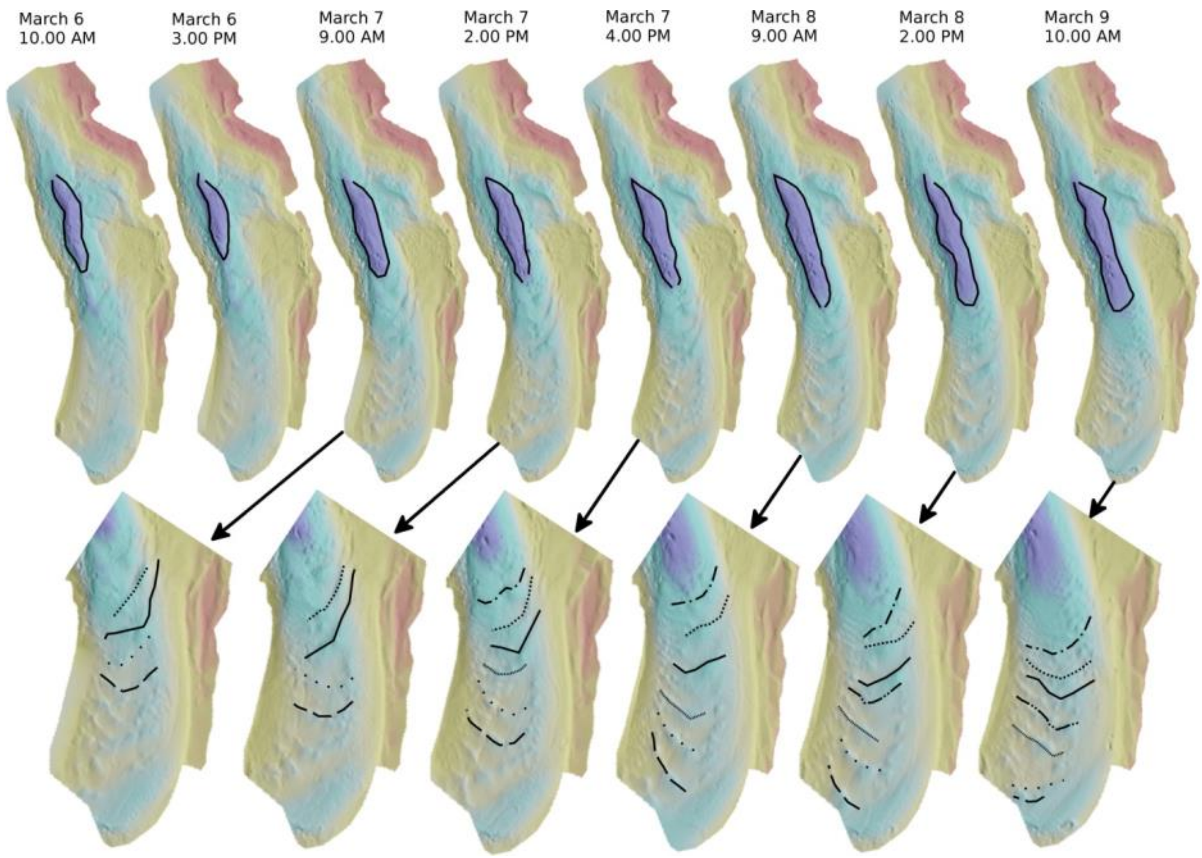

Figure 14. Evolution of the bed at Eminence during the 2008 HFE (data from Wright and Kaplinski, 2011) showing significant bed deformation and migration of bedforms over the timescale of hours to days.

In year 1, we propose to conduct this work in the pool immediately upstream from the water and sediment gaging station at RM 61, upstream from the confluence with the Little Colorado River and within Natal Origins Reach 4. In order to maximize the efficiency of the fieldwork, and minimize costs, this work will be conducted in conjunction with a Natal Origins field trip. This site has been mapped using MBES-derived bathymetry in May 2009, May 2012, August 2013, and May 2014. A well-developed bedform field is present (Fig. 15). We propose to map the same bedform fields repeatedly as many times as possible during a week, in conjunction with ADCP measurements along multiple transects, which have been shown to adequately characterize the near-bed velocity flow field responsible for mobilizing and transporting sediment as bedload under varying discharges. This intensive repeat mapping and sampling of an entire ~1 mile reach, near an existing long-term gaging site, and during multiple days with a range of flows, is the best strategy for compiling enough data to answer the suite of scientific questions posed above. Bedload fluxes will be estimated by applying to the MBES-derived data a suite of existing techniques, principally the migration of bedforms based on the Exner equation (Simons and others, 1965); cross-correlation of bedform crest locations (Engel and Lau, 1980; Duffy and Hughes-Clarke, 2005) and a hybrid method which purports to quantify both flux associated with bedform migration and bedform deformation (changes in shape) (McElroy and Mohrig, 2009).

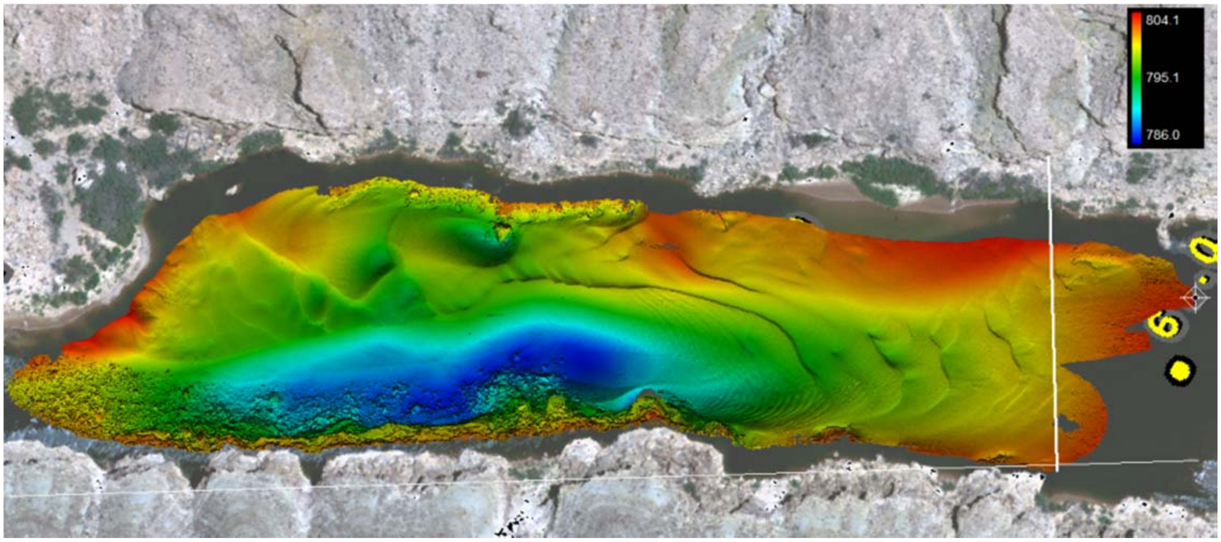

Figure 15. Bathymetry (measured in May 2014) of the sediment gaging pool at RM61. Repeat surveys of this area (in May 2009, May 2012, and August 2013) have revealed an active and consistently well-developed dune field.

Bed sediment grain size will be estimated using the techniques of Buscombe and others (in review) using the MBES acoustic backscatter data (Fig. 10). The goal of connecting to this work is to allow for bedload fluxes to be determined as a function of bed sediment type. For example, distinguishing between sand and gravel dunes is important so migrating gravel dunes do not contribute to the sand mass balance. The relative proportions of mobile sand and lag coarse deposits in an entire dune field would be estimated by extrapolating from the areal proportion of those two sediment fractions at the surface, as measured using acoustic techniques. It will also provide insight into bed condition as a function of bed sediment transport. In addition, high-resolution observations of bed sediment type are required to meet Objective 5 (bed state indicator model). Similarly, we will connect to ongoing efforts to monitor suspended sand loads (e.g. Topping and others, 2010). The major goal of this connection is to elucidate the extent to which sand is exchanged between bedload and suspended load volumes within and between individual flow events, within and between individual reaches, and at scales from individual bedforms to those relevant for calculating bed sand load.

We also propose to collect full water-column imaging from MBES at discrete locations above dunes in conjunction with both physical samples of suspended sediment and the 15-minute acoustic suspended sediment time-series at the gauging station at RM 61. This creates the possibility of calibrating MBES acoustic backscatter for suspended sediment concentration, making possible the mapping, in 3D, of the time-integrated field (spatially static) of suspended sediment, using the methods detailed in Jones (2003) and Simmons and others, (2010). Such information is a requirement of Objective 6 and enables us to answer questions related to the interaction of an evolving bedform field with a spatially non-uniform flow and sediment field, and the representativeness of suspended sediment measurements at discrete locations.

One of the outcomes of this project will be a test of the hypotheses described above. In doing so, we will generate a bedload sediment rating curve for the Colorado River in Grand Canyon based on routinely measured quantities (discharge and suspended sediment). This will lead to an informed methodology to account for bedload in sediment management operations and possibly to better understanding of the interaction between sandbars and bed load during low discharges.

We anticipate at least two major scientific products and at least one major management product. In addition, yearly reports and presentations at national-scale conferences will be produced. One scientific manuscript will deal exclusively with bed load fluxes through the Grand Canyon and its physical controlling factors. The second will focus on the relations between bed load and suspended load, and it will include a treatment of Grand Canyon sediment budgets including bedload. Finally, we will produce a document that makes recommendations for if and how to further incorporate bedload with sediment monitoring in the canyon.

Outcomes and Products

- Journal article on relation between bedload and suspended sediment load in the Colorado River (*lead author Graduate Student*).

Project Element 3.5. Control Network and Survey Support

Keith Kohl, Surveyor, USGS, GCMRC

Objectives

Ensure that all data collected in scientific investigations are correctly and consistently referenced to the National Spatial Reference System (NSRS) for reliable use in Geographical Information Systems (GIS).

Rationale/Justification

The overarching goal of this project element is to develop a sound process for establishing, maintaining, and verifying survey control in support of long-term monitoring within the CRE. Toward this end, GCMRC requires a control network and survey procedures that will yield reliable and consistent results now, while allowing for advances in theory and technology in the future. Importantly, the procedures must withstand changes in personnel that will inevitably occur over the life of the CRe monitoring programs.

An accurate geodetic control network is required to support nearly every aspect of this project as well as most other GCMRC monitoring projects. The purpose of the control network is to ensure that spatial data acquired on all projects are collected with accurate and repeatable spatial reference. The control network is essential to enable comparison among data sets collected by different methods and ensure that spatially referenced observations are repeatable and that all data are documented and archived appropriately. Projects that are directly dependent on the control network include this project, all other projects that use system-wide airborne remote sensing, archeological site monitoring, and vegetation monitoring. The remote sensing work is particularly dependent on accurate control operations, without which image data could not be compared accurately with ground-based measurements.

The control network is the set of monumented and documented reference points (benchmarks) that exist along the river corridor and on the rim together with the collection of observations that determine the relative and absolute positions of those points. Those points serve as the basis for referencing all ground- and air-based monitoring observations. Currently, the control network includes more than 7,000 GPS observations and more than 2,000 optical observations that determine the precise location of more than 1,300 benchmarks in the river corridor and on the canyon rim. This project includes work in three broad categories: (1) building the control network, (2) direct support of research and monitoring activities, and (3) storage and archival of the control database.

Combining conventional measurements (which reference gravity) with GPS measurements (which reference a geocentric ellipsoid) requires the reduction of field measurements to the ellipse. Variations of mass density will affect local gravity, deflection of the vertical, zenith angle measurements, and height determination. High-resolution geoid models set out to define these relationships. Identifying these interactions within the CRE is critical since diverse methods are used to determine positions, including remote sensing, conventional ground-based optical methods, Global Positioning System (GPS), and bathymetric surveys.

Combining the results of these various methods to derive a consistent set of coordinates requires a detailed knowledge of how these coordinates are derived, as well as the accuracy of the derivation. Coordinates, datum descriptions, and accuracy results are provided in a format compatible with Federal Geographic Data Committee (FGDC) delivery standards.

Proposed Work: Control Network

Primary tasks of building the control network include making GPS observations at new and existing benchmarks, and linking conventional traverses between the GPS monuments to determine positions and ellipsoid heights. Most segments of the river corridor now have a sufficient number of control points to support monitoring activities.

Determining accurate elevations requires addressing the difference that exists between ellipsoid heights, which are determined by GPS observations, and orthometric elevations (i.e. NAVD88), which can be determined only by gravity measurements or precise leveling. The deviation between ellipsoid height and orthometric height is modeled in a hybrid geoid model (Geoid12a) which combines GPS observations, gravity and optical leveling. The deviation can be as large as 10 cm over a distance of 1 km and affects our ability to determine river slope and develop longitudinal profiles. This, in turn, affects the accuracy of streamflow models. The challenge of determining accurate elevations in rugged topography is a major focus of the National Geodetic Survey (NGS). We have been encouraging the NGS to conduct a campaign of gravity measurements for the region; however, due to the remote location, low population, and difficult access, the geoid model in Marble and Grand Canyons is improving much slower than in high–use, populated areas.

We have made progress with these challenges by incorporating existing leveling measurements into the control network. In FY13–14 this involved the publication in the NGS database of 1046 newly adjusted NAVD 88 benchmarks throughout Grand Canyon www.ngs.noaa.gov/cgi-bin/ds_proj.prl, Survey Project ID: L27947). In FY15, these data will be analyzed to compare GPS observations with historical leveling observations to better define the relation between GPS heights and orthometric heights and enable more accurate measurements of elevation.

Additional leveling information is available in Glen Canyon, including a published level line with NAVD88 orthometric heights determined from differential leveling done in 1923 and adjusted by the NGS in 1992. In FY16, we will perform an analysis of the leveling data and evaluate height differences between previous and current control networks in Glen Canyon. The data provides an excellent opportunity to test the performance of both the hybrid geoid (Geoid12a) and the gravimetric geoid (USGG2012) in a steep canyon environment. Information gleaned from this study will be used to estimate elevation accuracies throughout the CRE.

A longitudinal profile study of the Colorado River through Glen, Marble, and Grand Canyons is scheduled for FY17. The study will use all available data to define the Colorado River water surface with accurate geodetic positions and elevations. Conventional traverse measurements will be used to evaluate geoid performance.

Proposed Work: Support of Research and Monitoring Projects

The two major projects that require survey support in 2015–2017 are the sandbar (Project Element 3.1) and sediment storage (Project Element 3.2) project elements and Project 4. The sandbar and sediment storage project elements described here rely on the accurate positions of hundreds of monuments to link measurements and confirm proper equipment setup and calibration. The topographic and bathymetric surfaces share the same datum and are referenced to the same monuments and coordinates as the remotely sensed data. The control network also supports remote sensing by determining the positions of well-defined points from independent sources of higher accuracy. This allows scientists and managers means to assess positional accuracy of data, maps, and products.

The scope of this survey support project element is to assist other GCMRC projects with survey knowledge, control infrastructure and equipment as need arises. The expertise of the survey staff is used in many data collection efforts including collecting, processing, and delivering reference base station data for overflight missions and supporting Streamflow, Water Quality, and Sediment Transport project (Project 2), and the Vegetation Monitoring project (Project 11). GNSS basestations are published (bluebooked) within the National Geodetic Survey Integrated Database (NGSIDB) (National Geodetic Survey, 2012). The budget for personnel time required for the collection of field data and processing for specific projects is incorporated in each individual project element.

Storage, Archival, and Documentation of the Control Network Database

The control network data are stored in a Microsoft Access database that is linked with the GCMRC GIS database. The survey staff works with GIS staff to maintain and update the database as needed.

Outcomes and Products – FY2015

- Control network adjustment for RM 0 to 30 (contributes to product in Project 3.2).
- Control network adjustment for eastern Grand Canyon (contributes to product in Project 3.2).
- Updates to the National Geodetic Survey Integrated Database (NGSIDB) of all available Height Modernization and Benchmark stations

Outcomes and Products – FY2016

- Control network adjustment for Glen Canyon (contributes to product in Project 3.2).
- Report/journal article on combining GPS observations and historical leveling data for more accurate elevations and updated geoid models (*lead author Kohl*).

Outcomes and Products – FY2017

- Control network adjustment for upper Marble Canyon (contributes to product in Project 3.2).
- Report/journal article on heights, control networks and datum changes in Glen Canyon, 1923 to 2015 (*lead author Kohl*).

D.3 Personnel and Collaborations

The project lead is Paul Grams. Daniel Buscombe is a post-doctoral fellow and Research Geologist with specialization in bed-texture characterization using underwater imaging and acoustics. Erich Mueller is a post-doctoral fellow and Research Hydrologist with specialization in geomorphology and sediment transport. Joel Sankey is a Research Geologist and remote sensing expert. Keith Kohl is the control network specialist and surveyor. Support is provided by Robert Ross and Robert Tusso who are term hydrologists, and Thomas Gushue who is the GCMRC GIS Coordinator. Ted Melis is a Physical Scientist with expertise in hillslope and debris flow process and linkages between physical science and ecology. David Topping is aa research hydrologist with GCMRC, and the Project 2 lead. Mike Yard is a Fishery Biologist with GCMRC. The GCMRC staff has management responsibility for the entire project and share responsibility for data collection, analysis, and reporting. Joseph E. Hazel, Jr, and Matt Kaplinski of Northern Arizona University are long-term collaborators on sandbar and sediment storage monitoring. David Rubin is a former USGS employee and long-time collaborator on sediment transport dynamics, currently serving as a Research Professor, University of California at Santa Cruz. Joe Wheaton is an Assistant Professor at Utah State University and an expert in collecting, processing, and analyzing digital elevation models. Brandon McElroy is an Assistant Professor at the University of Wyoming and an expert in bed form migration and bedload transport in sand-bedded rivers. Mark Schmeeckle is an Associate Professor at Arizona State University and an expert in fluid mechanics and computational modeling. David Varyu is a hydraulic engineer at the BOR Technical Service Center with expertise in hydraulic and sediment transport modeling. Robert Weber is a photogrammetrist with Pinnacle Mapping Technologies, Inc. Graduate students will work on the Rapid Survey project (3.1.3.), modeling project (3.3), and bedload project (3.4).

D.4 Deliverables

See "Outcomes and Products" listed by project element, above.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

Website showing repeat photographs showing effects of Fall 2012 HFE: http://www.gcmrc.gov/gis/sandbartour2012/index.html?

Website showing repeat photographs showing effects of Fall 2013 HFE: http://www.gcmrc.gov/gis/sandbartour2013/index.html?

Sandbar Monitoring Data: Sandbar topographic surveys and campsite surveys conducted fall 2012 and 2013. Reported at Annual Reporting Meetings and provided to Reclamation for inclusion in LTEMP analysis. Website to serve data is in development.

Sediment Storage Data (Channel Mapping): Data collected in 2013 for topographic/bathymetric map of RM 0 to 30: processing is nearly complete.

E.2. Completed Publications

Alvarez L.V, Schmeeckle M.W. 2013. "Erosion of River Sandbars by Diurnal Stage Fluctuations in the Colorado River in Marble and Grand canyons: Full-Scale Laboratory Experiments". River Research and Applications, 29: 839-854. doi:10.1002/rra.2576.

Buscombe, D., 2013, Transferable Wavelet Method for Grain Size-Distribution from Images of Sediment Surfaces and Thin Sections, and Other Natural Granular Patterns. Sedimentology, 60: 1709–1732.

Davis, P.A., 2013, Natural-color and color-infrared image mosaics of the Colorado River corridor in Arizona derived from the May 2009 airborne image collection, U.S. Geological Survey Data Series 780.

Draut, A.E. and Rubin, D.R., 2013, Assessing grain-size correspondence between flow and deposits of controlled floods in the Colorado River, USA: Journal of Sedimentary Research 83 (11), 962-973.

Grams P. E., 2013, A sand budget for Marble Canyon, Arizona--implications for long-term monitoring of sand storage change, U.S. Geological Survey Fact Sheet 2013–3074, 4 p., http://pubs.usgs.gov/fs/2013/3074/.

Grams P. E., D. J. Topping, J. C. Schmidt, J. E. Hazel Jr., and M. Kaplinski (2013), Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design, J. Geophys. Res. Earth Surf., 118, 361–381, doi:10.1002/jgrf.20050. http://onlinelibrary.wiley.com/doi/10.1002/jgrf.20050/full

Grams, P. E., and P. R. Wilcock (2013), Transport of fine sediment over a coarse, immobile river bed, Journal of Geophysical Research: Earth Surface http://onlinelibrary.wiley.com/doi/10.1002/2013JF002925/abstract.

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., Davis, P.A., 2014, Monitoring fine-sediment volume in the Colorado River ecosystem, Arizona—Construction and analysis of digital elevation models: U.S. Geological Survey Open-File Report 2014–1052, 29 p., http://dx.doi.org/10.3133/ofr20141052.

Kennedy, T. A., C. B. Yackulic, W. F. Cross, P. E. Grams, M. D. Yard, and A. J. Copp (2014), The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river, Freshwater Biology, 59(3), 557-572.

Mueller, E.R., Grams, P.E., Schmidt, J.C., Alexander, J.S., Hazel Jr., J.E., and Kaplinski, M., *accepted with revisions*, The influence of controlled floods on fine sediment storage in debris fan affected canyons of the Colorado River basin. Geomorphology.

Ross, R., and Grams, P.E., 2013, Nearshore thermal gradients of the Colorado River near the Little Colorado River confluence, Grand Canyon National Park, Arizona, 2010: U.S. Geological Survey Open-File Report 2013–1013, 65 p. (Available at http://pubs.usgs.gov/of/2013/1013/.)

Ross, R.P., and Vernieu, W.S., 2013, Nearshore Temperature Findings for the Colorado River in Grand Canyon, Arizona—Possible Implications for Native Fish: U.S. Geological Survey Fact Sheet 2013-3104, 4 p., http://dx.doi.org/10.3133/fs20133104.

E.3. Publications in progress

Alvarez L.V, Schmeeckle M.W., Grams P., *in prep.*, The Mechanics of Turbulent Flow in Lateral Separation Zones: Field Scale Detached Eddy Simulation Model, Water Resources Research.

Buscombe, D., Grams, P.E., Kaplinski, M.A., *in review*, Characterizing riverbed sediment using high-frequency acoustics 1: Spectral properties of scattering. Intended for Journal of Geophysical Research - Earth Surface.

Buscombe, D., Grams, P.E., Kaplinski, M.A., *in review*, Characterizing riverbed sediment using high-frequency acoustics 2: Scattering properties of Colorado River bed sediment in Marble and Grand Canyons. Intended for Journal of Geophysical Research - Earth Surface.

Buscombe, D., Rubin, D.M., Lacy, J.R., Storlazzi, C., Hatcher, G., Chezar, H., Wyland, R., and Sherwood, C., *accepted for publication*, Autonomous bed-sediment imaging-systems for revealing temporal variability of grain size. Limnology and Oceanography: Methods.

Buscombe, D., and others, *in prep.*, Mapping sandbar topography in Marble Canyon, AZ, using time-lapse imagery during controlled floods, Earth Surface Processes and Landforms.

Davis, P.A., Kohl, K.A., and Gushue, T.M., *in prep.*, Evaluation of Airborne ADS40 Photogrammetric Digital Surface Models for Monitoring the Colorado River Corridor below Glen Canyon Dam, Arizona.

Grams, P.E. and others, *in prep.*, A comprehensive sand budget for the Colorado River in Marble Canyon, Arizona: 2009-2012, Earth Surface Processes and Landforms.

Gushue, T., and others, *in preparation*, Photogrammetric methods for processing 1984 historical images.

Hadley, D.R. and Grams, P.E., *in prep.*, Geomorphology and vegetation change at sandbar campsites along the Colorado River, Marble and Grand Canyons, AZ: River Research and Applications.

Hadley, D.R., Grams, P.E., and Parnell, R., *in prep.*, Geomorphology and vegetation change at sandbar campsites along the Colorado River, Marble and Grand Canyons, AZ: U.S. Geological Survey Open-file Report.

Hazel, J.E., Jr., Kaplinski, M., Parnell, R., Grams, P., Ross, R., Hamill, D., and Kohl, K., *in prep.*, Sandbar Monitoring at Selected Sites in Colorado River in Marble and Grand Canyons, Arizona, 1990-2013: U.S. Geological Survey Scientific Investigations Report.

Hazel, J.E., and others, *in preparation*, Extending sandbar monitoring back in time using photogrammetry, digital terrain extraction and orthorectification of historical aerial imagery, Grand Canyon.

Kaplinski, M., Hazel, J.E., Jr., Parnell, R., Hadley, D., and Grams, P.E., *in review*, Colorado River Campsite Monitoring, 1998 – 2012, Grand Canyon National Park, Arizona: US. Geological Survey Open-file Report.

Kaplinski and others, *in prep.*, Monitoring fine-sediment volume in the Colorado River ecosystem, Arizona: Topographic and bathymetric maps of the Colorado River.

Ross, R.P. and Grams, P.E., Changes in Sandbar Area from Remote Sensing: 2002-2009, *in prep.*, U.S. Geological Survey Open-file Report.

Rubin, Topping, Grams, Tusso, Schmidt, Buscombe, Melis, and Wright, *in prep.*, What sediment grain size reveals about suspended-sediment transport in the Colorado River in Grand Canyon.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., Cagney, L.E., *in review*, Colorado River, vegetation, and climate: five decades of spatio-temporal dynamics in the Grand Canyon with river regulation.

Tusso, R., and others, *in prep.*, Bed-sediment grain size in selected monitoring reaches of the Colorado River in Grand Canyon: 2009-2012, U.S. Geological Survey Open-file Report.

E.4. Presentations at GCDAMP meetings

Buscombe, D. and others, Where is the sand? Using multibeam sonar to map sediment type in Marble Canyon: poster presentation at January 2014 Annual Reporting Meeting.

Grams, P.E. and others, Sand in Marble, Glen, and Grand Canyons: status and trends, oral presentation at January 2014 Annual Reporting Meeting.

Grams, P.E. and others, Sandbar Monitoring for November 2012 Controlled Flood: oral presentation at January 2013 Annual Reporting Meeting.

Gushue, T. and others, Extending sandbar monitoring back in time using photogrammetry, digital terrain extraction and orthorectification of historical aerial imagery, Grand Canyon, AZ: poster presentation at January 2014 Annual Reporting Meeting.

Hadley, D.R. and others, Geomorphologic and vegetation analysis at Colorado River campsites, Marble and Grand Canyons, AZ: poster presentation at January 2014 Annual Reporting Meeting.

Kaplinski, M. and others, Constructing a Morphologic Sediment Budget, With Uncertainties, for a 50-km Segment of the Colorado River in Grand Canyon: poster presentation at January 2014 Annual Reporting Meeting.

Mueller, E.R. and others, The effect of controlled floods on decadal-scale changes in channel morphology and fine sediment storage in debris fan-affected river canyons: poster presentation at January 2014 Annual Reporting Meeting.

Ross, R.P. and Grams, P.E., Using remote sensing to determine sandbar area from 1935-2009 within select reaches, Marble and Grand Canyons, AZ: poster presentation at January 2014 Annual Reporting Meeting.

Tusso, R. and Mueller, E.R., Effects of High Flow Events on sandbars along the Colorado River, Grand Canyon: poster presentation at January 2014 Annual Reporting Meeting.

E.5. Presentations at professional meetings

Alvarez L.V, Schmeeckle M.W. 2013. "Numerical Model of Turbulence, Sediment Transport, and Sediment Cover in a Large Cayon-Bound River". Presentation Type: Oral Presentation. Abstract ID: 1813508.. Final Paper Number: EP24B-07. American Geophysical Union, 2013 Fall Meeting, San Francisco, CA.

Alvarez L.V, Schmeeckle M.W. 2013. Numerical Model of Turbulence and Sediment Transport in Lateral Recirculation Zones Along the Colorado River in Grand Canyon. Presentation Type: Poster. 2013 CSDMS (Community Surface Dynamics Modeling System), Boulder, CO.

Alvarez L.V, Schmeeckle M.W. 2012. "Laboratory and numerical modeling of sandbar bank erosion, application to diurnal stage variations in Grand Canyon". Presentation Type: Oral Presentation. American Association of Geographers, 2012 Meeting, New York city, NY.

Buscombe, D., Grams, P.E., Kaplinski, M.A. 2013 Acoustic Scattering by an Heterogeneous River Bed: Relationship to Bathymetry and Implications for Sediment Classification using Multibeam Echosounder Data. American Geophysical Union Fall Meeting, San Francisco, Dec 2013

Grams. P.E., Buscombe, D., Hazel, J.E., Kaplinski, M.A., and Topping, D.J. (2013) Reconciliation of Flux-based and Morphologic-based Sediment Budgets. American Geophysical Union Fall Meeting, San Francisco, Dec 2013.

Kaplinski, M.A., Hazel, J.E., Grams. P.E., Buscombe, D., Hadley, D., and Kohl. K. (2013) Constructing a morphologic sediment budget, with uncertainties, for a 50-km segment of the Colorado River in Grand Canyon. American Geophysical Union Fall Meeting, San Francisco, Dec 2013.

Mueller, E.R., Grams, P.E., and Schmidt, J.C. (2013) The effect of controlled floods on decadal-scale changes in channel morphology and fine sediment storage in a debris-fan affected river canyon. Abstract EP33C-0923 presented at 2013 Fall Meeting, AGU, San Francisco, CA, 9-13 Dec.

Rubin, Topping, Grams, Tusso, Schmidt, Buscombe, Melis, and Wright, 2014, What sediment grain size reveals about suspended-sediment transport in the Colorado River in Grand Canyon: International Conference on the Status and Future of the World's Large Rivers, in press.

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G. Budget

Monitoring		Research																
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
									FY15								
							3	**Sandbars and Sediment Storage Dynamics**		**$549,700**	**$5,900**	**$46,000**	**$56,300**	**$500,600**	**$48,000**	**$118,100**	**$1,324,600**
X	X						3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$106,000	$2,000	$4,000	$26,600	$156,100	$48,000	$26,400	$369,100
X	X						3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$103,500	$0	$0	$0	$0	$0	$16,200	$119,700
		X					3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$18,700	$0	$0	$0	$20,000	$0	$3,500	$42,200
			X				3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$16,000	$0	$0	$0	$68,400	$0	$4,600	$89,000
X	X						3.2	Sediment storage monitoring	Grams et al.	$163,700	$2,000	$27,000	$29,700	$196,100	$0	$40,700	$459,200
			X				3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$64,700	$0	$0	$0	$25,000	$0	$10,900	$100,600
				X			3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100
X	X						3.5	Control network and survey support	Kohl	$77,100	$1,900	$15,000	$0	$0	$0	$14,700	$108,700

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY16																	
							3	**Sandbars and Sediment Storage Dynamics**		**$589,500**	**$5,900**	**$46,000**	**$92,400**	**$500,600**	**$20,000**	**$171,500**	**$1,425,900**
X	X						3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$109,100	$2,000	$4,000	$27,900	$156,100	$20,000	$35,200	$354,300
X	X						3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$107,200	$0	$0	$0	$0	$0	$22,900	$130,100
		X					3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$43,000	$0	$0	$0	$20,000	$0	$9,800	$72,800
			X				3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$16,300	$0	$0	$0	$68,400	$0	$5,500	$90,200
X	X						3.2	Sediment storage monitoring	Grams et al.	$167,000	$2,000	$27,000	$64,500	$196,100	$0	$61,400	$518,000
			X				3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$67,500	$0	$0	$0	$25,000	$0	$15,100	$107,600
				X			3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100
X	X						3.5	Control network and survey support	Kohl	$79,400	$1,900	$15,000	$0	$0	$0	$20,500	$116,800

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
							3	**Sandbars and Sediment Storage Dynamics**		**$611,600**	**$5,900**	**$46,000**	**$95,800**	**$500,600**	**$20,000**	**$223,000**	**$1,502,900**
X	X						3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$114,200	$2,000	$4,000	$29,100	$156,100	$20,000	$45,600	$371,000
X	X						3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$110,300	$0	$0	$0	$0	$0	$30,200	$140,500
		X					3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$44,500	$0	$0	$0	$20,000	$0	$12,800	$77,300
			X				3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$15,900	$0	$0	$0	$68,400	$0	$6,400	$90,700
X	X						3.2	Sediment storage monitoring	Grams et al.	$174,700	$2,000	$27,000	$66,700	$196,100	$0	$79,900	$546,400
			X				3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$71,000	$0	$0	$0	$25,000	$0	$20,200	$116,200
				X			3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100
X	X						3.5	Control network and survey support	Kohl	$81,000	$1,900	$15,000	$0	$0	$0	$26,800	$124,700

Project 4. Connectivity along the fluvial-aeolian-hillslope continuum: quantifying the relative importance of river-related factors that influence upland geomorphology and archaeological site stability

Initial Estimate: FY15: $185,600; FY16: $412,900; FY17: $404,700

GCDAMP Funding: FY15: $185,600; FY16: $384,000; FY17: $384,500

Other BoR Funding: FY15: $150,000; FY16: $150,000; FY17: $186,000

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B. Project Summary

The rate and magnitude of wind transport of sand from active channel sandbars to higher elevation valley margins potentially affects the stability of archaeological sites and the characteristics of other cultural and natural resources. The degree to which valley margin areas are affected by upslope wind redistribution of sand is called “connectivity”. Connectivity is affected by several factors including the sand source as well as physical and vegetative barriers to sand transport. The primary hypothesis of this project is that high degrees of connectivity lead to potentially greater archaeological site stability.

This project is responsive to recommendations from stakeholders in the Glen Canyon Dam Adaptive Management Program. The Bureau of Reclamation, the National Park Service, and the tribes, collectively have identified the need for science that will improve understanding of how cultural resources are linked to modern river processes. This project proposal is composed of two integrated elements; the first (4.1) is a research element, and the second (4.2) is a monitoring element. The research element (4.1) consists of three sub-elements that are landscape scale analyses that will examine the connectivity between attributes of the active channel and geomorphic processes and patterns at higher elevations (above the 45,000 ft^3/s stage) at several temporal and geographic scales. In the monitoring element (4.2), a year (2015) will be invested to develop and draft a long-term monitoring plan to evaluate if and how much the interactions between fluvial, aeolian, and hillslope processes affect the condition of cultural resource sites in the Colorado River corridor. The monitoring plan will be drafted by USGS scientists with close collaboration from tribes, National Park Service, and Bureau of Reclamation. The monitoring plan will be implemented in years 2 and 3 (2016 and 2017, respectively) of the triennial work-plan effort.

C. Background

C.1. Scientific Background

The environmental processes and factors that contribute to the current condition of cultural resources in the CRe are complex. Because the vast majority of archaeological sites in the CRe are situated well above the elevation reached by 25,000 ft^3/s river flows (Sondossi and Fairley, in revision), effects of dam operations on cultural sites are mainly indirect and manifest themselves through diffuse effects to the larger terrestrial ecosystem (Fairley and others, 1994; Fairley and Sondossi, 2010). The 1995 Environmental Impact Statement on the Operations of Glen Canyon Dam (USDI 1995) identified 336 sites in Grand, Marble, and Glen Canyons that were directly or indirectly affected by dam operations. These archaeological sites are situated in or on Holocene fine-sediment fluvial deposits derived from the Colorado River that were formed either before or after completion of Glen Canyon Dam (GCD).

Interest in the potential of dam operations to affect erosion rates at cultural resource sites in the CRe dates back to the early 1980s, when NPS archaeologists observed an increase in the amount and severity of gullying at archaeological sites (Hereford and others, 1991; Fairley, 2003). This topic was also identified by the Hopi Tribe as an important issue, because these processes influenced the Hopi's perspective on whether mitigation of potential dam effects to archaeological sites would, or would not, be appropriate to undertake (L. Kuwanwisiwma, personal communication, 1990, to H. Fairley). In 1989, a decision by the Department of Interior to undertake research on the downstream effects of Glen Canyon Dam resulted in the initiation of several studies focused on mapping the geomorphic context of archaeological resources and the geomorphic processes acting on those resources (Hereford and others, 1991, 1993, 1996; Lucchitta, 1991). This initial phase of research led to the publication of several detailed surficial geology maps that emphasized the distribution of Holocene deposits in areas of high cultural resource density, plus several reports documenting changes in the post-dam environment (Hereford and others, 1993, 1996; Hereford, Burke and Thompson, 1998, 2000a, 2000b; Lucchitta, 1991).

Subsequent work (e.g., Draut and others, 2005, 2010; Draut and Rubin, 2008; Collins and others, 2008, 2009, 2012; Draut 2012) has collectively indicated that a post-dam reduction in fine sediment supply (Topping and others, 2003) contributed to a reduction in active channel sandbars that are available for transport to high elevation sand deposits where archaeological sites are often located (Draut, 2012). This same phenomenon appears to have also reduced the resilience of the upland landscape to weather-induced erosional impacts, as illustrated, for example, by the fact that locations with less high elevation sand have greater prevalence of gullies (Sankey and Draut, 2014). Draut (2012) and Draut and Rubin (2008) proposed that the upland sand deposits in the river corridor can be broadly grouped into those with modern sand supply by wind from river sandbars (modern-fluvial-sourced sand deposits, hereafter referred to as MFS) and those that have not received sand in post-dam time, and received their most recent major sediment replenishment from deposits associated with the 1921 flood of 170,000 ft^3/s (relict-fluvial-sourced deposits, hereafter referred to as RFS; Draut, 2012). Available evidence indicates that sediment supply limitation and lack of large floods, in conjunction with increased biological soil crust cover, has further reduced mobility of high-elevation sand deposits, with multiple interacting effects to surface erosion processes in and adjacent to archaeological sites and associated Holocene deposits (Draut, 2012). Work conducted in 2013 and 2014 (Project J of the FY 13/14 Biennial Work Plan) described the extent to which aeolian sand provides a protective cover to the ground surface of archaeological sites, and even infills – with potential to mitigate – eroding gullies within and adjacent to archaeological sites (Sankey and Draut, 2014; Collins and others, in review). Very recent work has also qualitatively described the role, in many locations, of riparian vegetation that produces a barrier to the onshore and upslope transport by wind of MFS aeolian sand (East, 2014). Riparian vegetation can thus segregate the general category of MFS landscapes into additional categories that reflect the varying degrees to which sites receive modern sand resupply based on whether vegetation impedes aeolian transport of sand from a fluvial sandbar to an archaeological site.

Recent work has quantified the long-term trend of the lowering and encroachment of riparian vegetation into the former active channel in response to decreased flood magnitude and duration (Sankey and others, in review). During the same post-dam timeframe, periods of increases and decreases in xeric (upland, desert) vegetation have occurred at higher stage-elevations in response to regional climate and episodes of drought (Sankey and others, in review). While environmental factors, including fluvial sources of aeolian sand and riparian vegetation, have been identified previously (Draut, 2012; Collins and others, in review) as important controls on connectivity along the fluvial-aeolian-hillslope continuum, the relative prevalence and importance of many of these controls have not been explicitly tested over large geographic extent or multi-temporal scales. We define connectivity (Merriam, 1984) as the "degree to which a landscape facilitates or impedes movement among resource patches" (Taylor and others, 1993), and focus specifically on the potential for movement of sand by wind between active channel sandbars to higher elevation sand landscapes. Potentially important controls on connectivity include: upwind sand bars that are resupplied by controlled floods (administratively referred to as High Flow Experiments or HFEs); alternative sediment sources including tributary channels/mouths, bare sediment surfaces on terrace risers, campsites and other high user impact areas; vegetation (either barriers positioned between fluvial sand bars and upland areas or cover of formerly open sand [source] areas); and, topographic barriers such as rock outcrops and debris fans.

In addition to the recent work conducted at landscape scales that has identified some of the important controls on connectivity along the fluvial-aeolian-hillslope continuum, site-specific monitoring has identified that many archaeological sites are dominated by erosion processes caused by discrete runoff erosion events that can lower the ground surface several centimeters over areas as large as tens to hundreds of square meters (Collins and others, 2012; Collins and others, in review). In addition to aeolian influx of fluvial sediment, potentially important controls on site erosion also include proposed mitigation treatments such as the installation of check dams that might control expansion and propagation of gullies. Possible vegetation treatments that remove or reduce dense vegetation barriers also might be employed to promote aeolian transport of fluvially sourced sand to higher elevations. Defoliation of tamarisk caused by the recent spread of the tamarisk beetle (*Diorhabda carinulata*) is also a contemporary environmental factor that might increase the potential for aeolian sand transport through vegetation barriers, and may have effects similar to vegetation removal treatments.

Most recent small spatial scale monitoring work in Grand Canyon has been conducted with terrestrial (ground-based) lidar remote sensing. Collins and Kayen (2006) first demonstrated lidar's potential utility for documenting topographic and vegetation change in the CRe. A phased program of research and development was initiated between 2006 and 2010 towards implementation of a long-term core-monitoring program (Fairley and others, 2007). The first phase of this project (Phase I) began in spring 2006 and initially focused on completing a comprehensive assessment of the geomorphic and archaeological attributes of 232 river corridor sites (O'Brien and Pederson, 2009a) to characterize the range of variability in these archaeological sites and to aid in the selection of an appropriate sample for a future pilot monitoring program (Vance and Smiley, 2011). Phase I involved testing a variety of survey techniques, including terrestrial lidar, as potential tools for measuring change in resource condition (Collins and others, 2008).

The applicability and utility of monitoring archaeological sites using terrestrial lidar was subsequently demonstrated at 13 sites in Grand Canyon (e.g., Collins and others, 2008, 2009, 2012). Collins and others, (2008) showed that terrestrial lidar technology could be used to collect data as accurate as or better than previously evaluated total station topographic surveys, while minimizing impacts to the sites being monitored; total station techniques had been previously evaluated as a potential monitoring approach (Leap and others, 2000). Several criticisms of the total station method that led to the investigation of lidar as an alternative tool included the fact that total station surveys often resulted in significant impacts (e.g., trampling) to sites, and the resolution and measurement error in repeated surveys was potentially greater than the amount of change targeted for detection. The work of Collins and others, (2008) documented that entire site areas could be monitored with lidar with minimal impact. Initially, Collins and others (2009) documented surface-elevation changes greater than 8 cm at 6 of 9 sites monitored between September 2006 and September 2007. Since these initial field studies, advances in lidar technology have resulted in laser scanning devices with greater accuracy and new software with improved potential to measure small-scale (centimeter-level) topographic change (Collins and others, 2012). Incorporating these advances, Collins and others (2012) collected multiple comparable lidar data sets at 11 sites during a 5-year period. This effort demonstrated that (1) land surface change of ~ 5 cm could be reliably and accurately detected over large areas, and (2) it is possible to link observed changes to specific geomorphic processes. There is a finite limit to the sample size of sites that can be surveyed with lidar at this level of detail in a single monitoring effort, due to logistics. Therefore the question persists of how to most appropriately extrapolate from an inherently small set of detailed lidar measurements to the large population of archaeological sites.

Work completed in 2013 and 2014 incorporated additional lidar surveys into a synthesis of more than 5 years of surface-elevation data and change detection at archaeological sites in Grand Canyon and sought to link measured landscape changes to meteorological conditions (Collins and others, January 28, 2014 GCMRC Annual Reporting Meeting, and Collins and others, in review). Key findings of this work were that erosion dominates the landscape response at most sites, in large part because high intensity, runoff producing storms that sometimes induce erosion and gullying are relatively common within Grand Canyon. Precipitation records from the past century indicate that storms comparable to those that induce significant overland flow occur during years of average and wet conditions. Erosion-inducing storms occur at individual sites with frequencies that range from approximately once per year to once per decade, and results suggest that such storms occur at a majority of sites at least once every 2-3 years. The synthesis also identified the influx of aeolian sand – and specifically the infilling of individual gullies by aeolian sand – as a key landscape process that can mitigate erosion and the formation and propagation of gullies.

Change detection with lidar surveys identifies magnitude of topographic change and type of change, whether net erosion or deposition. However, it is also important to understand whether detected changes represent progressive or potentially reversing geomorphic change. Hillslope erosion and gullying in valley margins of the canyon are viewed as geomorphically progressive changes that in archaeological sites can result in net erosion in time. The key geomorphic process identified to date with potential to reverse this progressive change is influx of aeolian sand. Collins and others (2012, in review) have attributed changes detected with lidar surveys to one of several types of geomorphic change that are either runoff erosion, runoff deposition, aeolian erosion, or aeolian deposition. From the magnitude of changes attributed to each of these types of geomorphic change, it is possible to infer the degree of progressive vs. potentially reversing geomorphologic change at an individual site or sample of sites. However, it is still difficult to accurately extrapolate these observations to a more general understanding of the relative degree of progressive vs. reversing geomorphic processes for the population of archaeological sites, without a framework, such as an archaeological site classification system, for doing so.

In conjunction with the work in 2013 and 2014 that was conducted at landscape scales (Sankey and Draut, 2014) and site-specific scales (Collins and others, in review) and that quantified the importance of aeolian influx to gullied archaeological sites, additional novel work developed a system for classifying archaeological sites based on the degree to which the sites could potentially receive windblown sand from recent controlled floods (East, 2014). The classification of additional archaeological sites is currently ongoing and is anticipated to be completed in 2014 for sites within Grand Canyon National Park. All river-corridor archaeological sites will be classified based on an evaluation of geographic position relative to visible recent flood-sediment deposits, measured or inferred local prevailing wind directions, and identification of any potential barriers to aeolian sand transport between flood deposits and archaeological sites. The classification system identifies whether a site's geomorphic context includes river-derived sediment—either fluvial, aeolian, or both. The system also identifies whether barriers exist that could limit the aeolian transport of upwind fluvial sediment by wind to archaeological site(s). There are 5 types of sites included in the classification:

> Type 1: Sites with an adjacent, upwind fluvial sediment deposit formed by a recent high flow, and no evident barriers that would hinder aeolian sand transport from the flood deposit toward the archaeological site.
>
> Type 2: Sites with an upwind sediment deposit formed by a recent flood, but with a barrier separating the flood deposit from the archaeological site. These barriers were interpreted to potentially limit aeolian sand transport from the fluvial deposit toward the archaeological site. Such barriers may not entirely eliminate sand movement from fluvial deposit to archaeological site, but are interpreted as likely to inhibit aeolian sand transport.
>
> 2a: Vegetation barrier present (may be riparian or higher-elevation, non-riparian upland vegetation).
>
> 2b: Topographic barrier present (most often a tributary channel, but in several cases a steep bedrock cliff or large boulders).

2c: Both vegetation and topographic barriers present.

Type 3: Sites at which a recent flood did not deposit sediment upwind of site, even though flood water had been present at an upwind location relative to the archaeological site (where an upwind shoreline exists for a recent controlled flood).

Type 4: Sites at which there is no upwind shoreline that could allow deposition from a recent controlled flood, but whose geomorphic context does involve river-derived sand deposited by pre-dam floods.

Type 5: Sites in the river corridor whose geomorphic context is not dependent on Colorado River-derived sand, such as those situated on bedrock or talus.

The classification of all archaeological sites within the river corridor of Grand Canyon National Park will be completed in 2014 and presented in the final report of “Project J” of the 2013 and 2014 GCMRC biennial workplan. One purpose of completing the classification for all river corridor sites within Grand Canyon National Park is to answer the question of “what proportion of sites in the river corridor are affected by river-derived sand and potentially receive windblown sand from recent controlled floods?”. A summary of the classification of a subset of the sites within Grand Canyon National Park is provided in Figure 1 (previously presented by Sankey and others, and Fairley and others, January 28, 2014 GCMRC Annual Reporting Meeting). While Figure 1 only pertains to a subset of all sites (197 sites had already been classified as of winter 2014 when Figure 1 was generated), it does indicate that a substantial number of river corridor sites (e.g., those classified as types 1 or 2) are linked to modern river processes with potential to receive windblown sand from recent controlled floods.

For the purposes of this proposal, we have considered the recent synthesis of 5 years of monitoring surface-elevation changes at 13 archaeological sites in Grand Canyon (Collins and others, in review) in the context of the site classification system (Figure 2). We note that this evaluation presently includes only a limited sample size which can lead to large uncertainties in estimates (e.g., note the large standard errors for many of the mean volume change bars plotted in Figure 2), and that increasing the number of sites available for such evaluations is one of the goals of the work we propose herein. Some of the largest surface elevation changes attributed to rainfall events – and including erosion and deposition by aeolian and overland flow transport – occurred at sites classified as type 1. Upwind fluvial sediment deposits formed by recent controlled flood(s) occur at these type 1 sites, and there were no barriers to hinder aeolian sand transport from the flood deposit toward the archaeological sites. However, fewer than half of these type 1 sites (two of the five type 1 sites; Figure 2) exhibited measureable aeolian deposition during the period of analysis. Moreover, a majority of the sites for which detailed data are available (8 of the 13 total sites), encompassing a variety of classes, had measurable aeolian erosion (deflation). Thus, interpretation of the site-specific surface elevation changes in the context of the archaeological site classification suggests that most sites of all classes are likely not transport limited with respect to aeolian processes (i.e., wind energy is often sufficient for transport). However, apparently even the most favorably positioned sites (e.g., type 1) with respect to fluvial sources of aeolian sand can still be lacking in either sediment source and/or possibly the right temporal and spatial interaction of wind energy and sediment availability to cause net long-term deposition and improve the chance of archaeological-site preservation in place.

Clearly, the classification system developed in 2013 and 2014, and the actual classification of archaeological sites, creates an important framework that should be further evaluated as a guide for future monitoring and research efforts. In particular, the classification provides scientists and managers with hypotheses that can be tested concerning the expected future landscape response of individual archaeological sites relative to dam operations and high flow events. The classification also promotes hypothesis testing concerning the future landscape response of individual sites to the potentially interacting effects of dam operation and high flow events with contemporary and possible future mitigation efforts such as erosion control check dams and riparian vegetation reduction treatments.

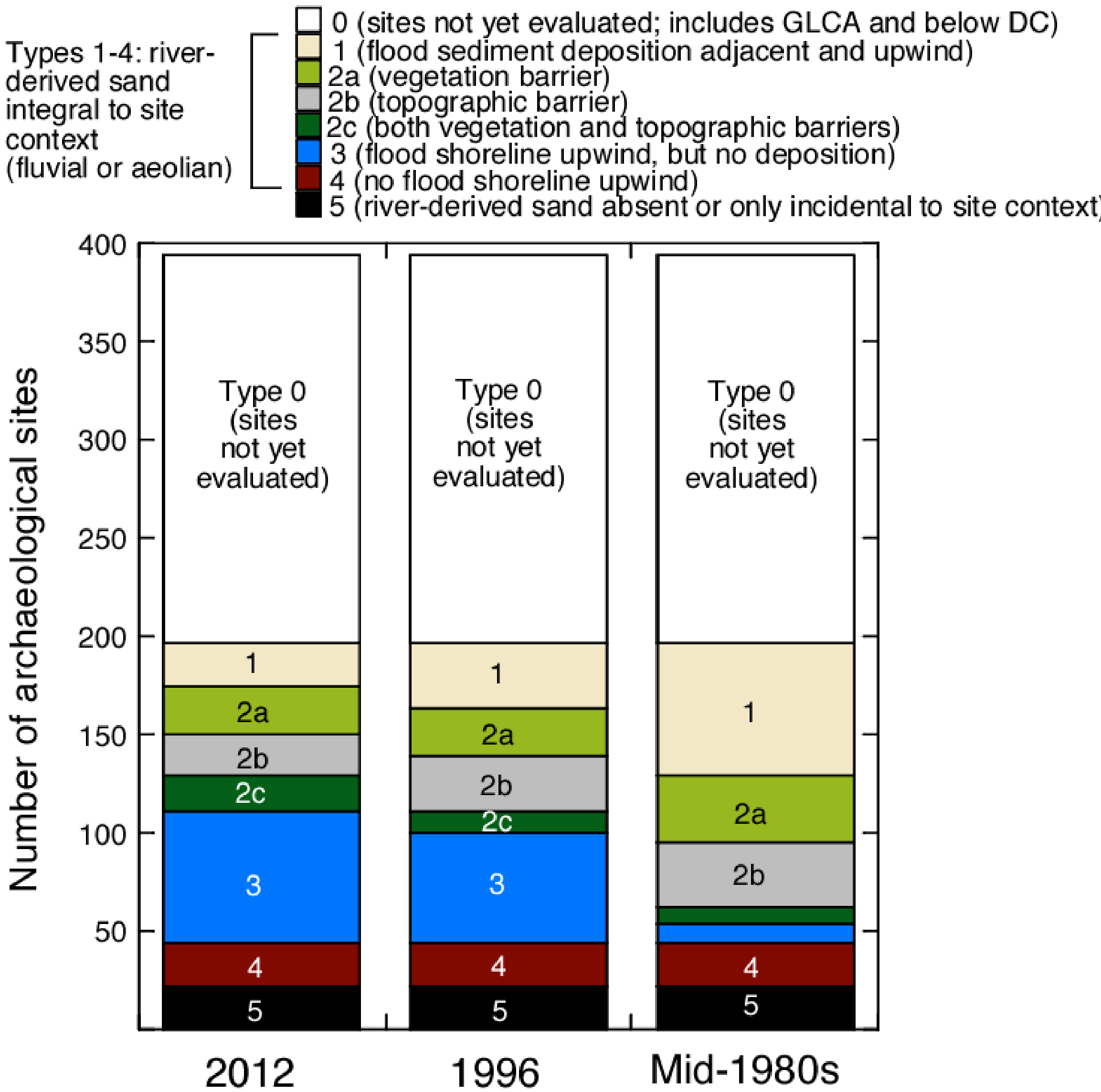

Figure 1. Summary of archaeological site classifications completed as of winter 2014 for a subset of Grand Canyon National Park river-corridor sites (previously presented by Sankey and others, and Fairley and others, January 28, 2014 GCMRC Annual Reporting Meeting). Note that the classification of all river-corridor archaeological sites within Grand Canyon National Park (> 350 sites) will be completed in 2014 and presented in the final report of "Project J" of the 2013 and 2014 GCMRC biennial workplan.

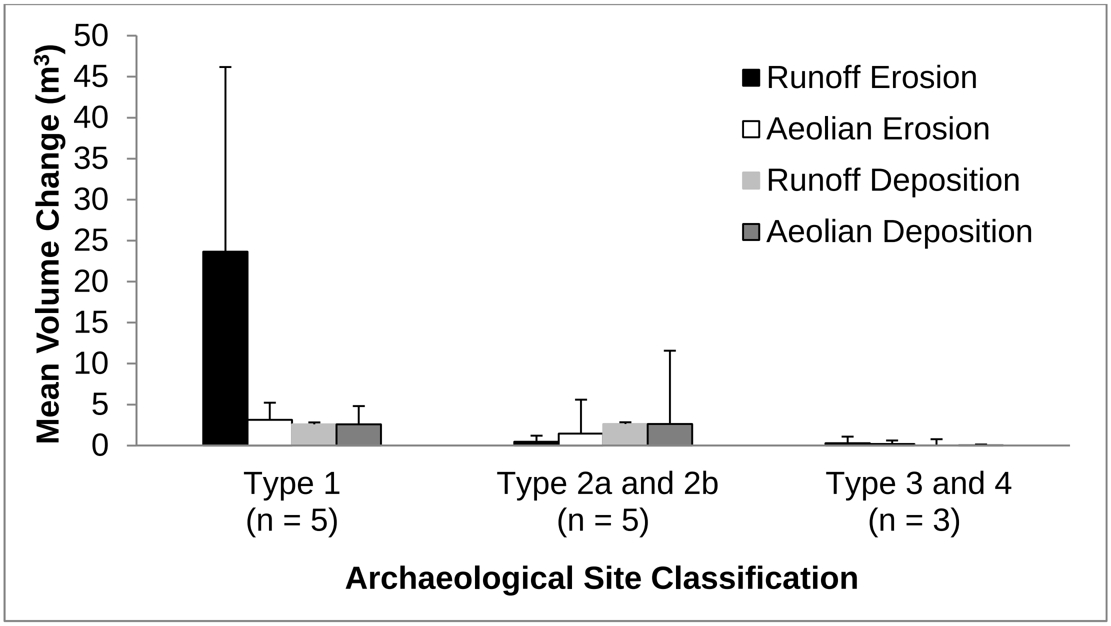

Figure 2. Volumetric surface change (by type and process) at archaeological sites, measured with ground-based lidar, and summarized by archaeological site class. Individual site change data are from Collins and others (in review) and are summarized by classes. Changes were determined at 1-3 year intervals for 13 sites between 2006 and 2010. Error bars show the standard error of the mean for n sites.

C.2. Management Background

Project 4 has been designed to be responsive to the goals of the GCDAMP, the monitoring requirements of the Grand Canyon Protection Act, the recommendations of the 2000 PEP (Doelle, 2000) and the 2007 Legacy Monitoring Data review panel (Kintigh and others, 2007). Project 4 has also been designed to be responsive to the needs of DOI agencies related to compliance with Section 106 and Section 110 of the National Historic Preservation Act for assessing effects of dam operations and effectiveness of experimental management actions such as HFEs, as well as the effectiveness of other non-flow management actions that may be initiated in the future to achieve the management goals for *in situ* preservation of archaeological sites.

When BOR decided to modify operations at Glen Canyon Dam in the early 1980s in order to increase peaking power generation, they initiated a series of environmental discussions and studies that led to development of an EIS and Record of Decision under the National Environmental Policy Act (USDOI 1995, 1996) and a programmatic agreement (PA) under the National Historic Preservation Act, all three of which included provisions to continue monitoring and researching effects of dam operations on archaeological sites and other cultural resources. Prior to these events, Grand Canyon National Park (GCNP) archeologists had been monitoring cultural sites in the river corridor since the late 1970s, using a monitoring approach that was designed to document the presence or absence of visitor use impacts and other types of threats and disturbances (Kintigh and others, 2007). These threats and disturbances included observations about erosion that potentially compromised the integrity of cultural sites. The NPS monitoring approach was subsequently incorporated as the interim approach for monitoring dam effects under the PA. This approach relied on assigning sites by categorical monitoring criteria. Observations of change were supplemented with repeat photographs of impacted areas, and maps were drawn to show locations of specific impacts. Monitoring was performed to meet the Park's compliance obligations under Section 110 of the National Historic Preservation Act (NHPA), to meet the section 106 requirements of BOR, and to identify sites that might require excavation or other forms of treatment to preserve their cultural, historic, and scientific values. The current NPS monitoring approach, which was developed by the Grand Canyon Cultural Resource Program in 2011 (Dierker and Brennan, 2011), has peer-reviewed monitoring protocols and mitigation protocols that guide monitoring and treatment activities in the park. The current NPS protocols supersede and improve monitoring efforts as prescribed under the Archeological Sites Information System (ASMIS).

In 2000, a cultural resources Protocol Evaluation Panel (PEP) recommended redesigning the PA monitoring program to focus more specifically on monitoring the effects of dam operations and evaluating the efficacy of erosion control efforts (Doelle, 2000). Although effects of dam operations were not specifically defined by the PEP, it is clear from the context of discussion in the PEP report that effects of dam operations were thought to be changes in the physical condition of archaeological sites that result from the direct inundation of sites and increases in rates of erosion that result from sediment supply limitations due to the presence and operation of Glen Canyon Dam. Although the PEP criticized the "overly narrow focus, adoption, and reliance on the 'base-level' hypothesis developed by Hereford et al.", geomorphologists on the panel recognized that "dam operations must contribute to the spatial and temporal variability in rates of erosion of deposits along the river corridor" to some unknown degree. They also noted that the hypothesis that aeolian influx of river-derived sand can affect rates of erosion of deposits along the river corridor, as proposed by Thompson and Potochnik (2000), "had not been adequately tested" and that "broader research on the topic would be useful." Thus, the PEP felt that it was important to structure the future monitoring program to distinguish and track the effects of dam operations separately from other non-dam-related impacts that can also affect cultural site condition, such as social trailing and artifact loss due to visitation. Specifically, the PEP recommended that the monitoring activities of the NPS and GCMRC should be integrated and refocused to: (1) evaluate the effectiveness of long-term management strategies (including treatments designed to control/minimize dam-related erosion) and (2) evaluate effects of different flow regimes on archaeological sites and other cultural resources such as Traditional Cultural Properties (TCPs). The PEP noted that "monitoring should be designed and organized to serve as the basis for periodic quantitative evaluations of the effect of dam operations, effectiveness of erosion control methods, and development of treatment plans". These recommendations were later echoed and further refined by the members of the legacy monitoring review committee (Kintigh and others, 2007), who emphasized the need for "unpacking the concept of site condition" to distinguish dam-related effects from other sources of impacts to cultural sites and for developing an explicit model to describe our understanding of how dam operations affect site condition, and then design a monitoring protocol that could explicitly test and evaluate the model.

Throughout the history of the GCDAMP, there has been ongoing discussion and considerable debate about the need for monitoring programs in general and what purpose(s) monitoring is supposed to serve. In general terms, monitoring can serve a broad variety of purposes (Hellawell, 1991):

- To assess the effectiveness of policy or legislation;
- To comply with regulatory requirements (performance or audit function); and,
- To detect incipient change ("early warning system").

Noon (2003) proposed an additional reason: to "assess the value and temporal (or spatial) trend of those indicators that characterize the state of an ecological system". In the GCDAMP generally, and in the cultural program arena specifically, all of these reasons have been cited as driving the need for monitoring (GCDAMP, 2003). Additionally, there is concern with meeting legal mandates, such as those identified in the Grand Canyon Protection Act (GCPA), which calls for "long term monitoring programs and activities that will ensure that Glen Canyon Dam is operated in a manner consistent with that of Section 1802." Section 1802 requires that the dam be operated in such a manner as to "protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established including, but not limited to natural and cultural resources and visitor use." In addition, there are legal obligations embedded within the National Historic Preservation Act (NHPA) that require federal agencies to consider effects of their actions on cultural resources (NHPA, Section 106) and also for the responsible land manager to identify, evaluate, and protect historic properties under their care (NHPA, Section 110). While monitoring is not specifically required for compliance with NHPA, monitoring is routinely implemented as a component of Section 106 compliance programs to assess effects of management actions or to evaluate the effectiveness of mitigation measures.

In the 2003 Strategic Plan (GCDAMP, 2003), GCDAMP stakeholders distinguished two monitoring categories: "Core Monitoring" and "Effects Monitoring". The GCDAMP developed the following definition of core monitoring:

> *Core monitoring consists of consistent, long-term, repeated measurements using set protocols and is designed to establish status and trends in meeting specific management objectives. Core monitoring is implemented on a fixed schedule regardless of variable factors or circumstances (e.g., water year, experimental flows, temperature control, stocking strategy, non-native control, etc.) affecting target species.*

Effects monitoring, on the other hand, was defined as:

> *… the collection of data associated with an experiment performed under the Record of Decision, an unanticipated event, or other management action. Changes in resource conditions measured by effects monitoring generally will be short-term responses. The purpose of effects monitoring is to supplement the fixed schedule and variables collected under core monitoring. This will both increase the understanding of the resource status and trends and provide a research opportunity to discover the effect of the experiment or management action.*

The project described here will implement monitoring protocols to address both "core monitoring information needs" (CMINs) and "effects information needs" (EINs) for cultural sites in Glen and Grand Canyons. The highest priority CMIN for historic properties, as revised by the Cultural Resource Ad Hoc Group (CRAHG) and adopted by the Science Planning Group (SPG) of the GCDAMP in the fall of 2005, is:

- **CMIN 11.1.1 (**SPG revised**).** Determine the condition and integrity of prehistoric and historic sites in the CRe through tracking rates of erosion, visitor impacts, and other relevant variables. Determine the condition and integrity of TCPs in the CRe.

In 2007, an expert panel reviewed the previous PA monitoring protocols and existing NPS monitoring data and developed recommendations for potentially incorporating these “legacy” monitoring data into future monitoring programs for the GCDAMP (Kintigh and others, 2007). Among several recommendations, the panel recommended that the monitoring program be redesigned to “unpack” the concept of site condition and separate out the factors affecting site condition that are potentially dam-related from those that are not (Wood and Johnson, 1978; Wildesen, 1982; Jones, 2007). The panel suggested that data from historical photographs might be productively mined in the future to evaluate changes that have already occurred to the sites through time. In addition, the reviewers suggested exploring the use of lidar technology as a tool for measuring and tracking ongoing surface changes at archaeological sites that are potentially linked to dam operations. At the same time, the panel recommended developing a model reflecting current understanding of how dam operations affect archaeological site condition, and to use the monitoring program to evaluate whether model predictions conform to monitoring results. The current proposal incorporates all of these recommendations.

This project is designed to address two primary Strategic Science Questions (SSQs) identified in the 2007 Monitoring and Research Plan (GCMRC, 2007):

- **SSQ 2-1.** Do dam-controlled flows affect (increase or decrease) rates of erosion and vegetation growth at archaeological sites and TCP sites in the CRE, and if so, how?
- **SSQ 2-4.** How effective are various treatments (e.g., experimental flows, check dams, vegetation management, etc.) in slowing rates of erosion at archaeological sites over the long term?

A monitoring program is also essential for determining whether management actions designed to stabilize or improve site conditions are working as intended. Therefore, this project also directly addresses EIN 11.1 (formerly CMIN 11.1.2 of the GCDAMP Strategic Plan, subsequently re-designated by CRAHG/SPG as EIN 11.1):

- **EIN 11.1.** Determine the efficacy of treatments for mitigation of adverse effects to historic properties.

Additionally, this project addresses a general GCDAMP research information need (formerly identified as CMIN 11.1.4 in the 2001 GCDAMP Strategic Plan):

> ***How effective is monitoring, what are the appropriate strategies to capture change at an archaeological site – qualitative, quantitative?***

The desired future conditions (DFCs) for archaeological sites articulated by AMP stakeholders and DOI management agencies identify preservation in place as the desired goal for archaeological sites and identify rates of erosion or deposition as one metric for assessing whether desired future conditions are being achieved. The DFCs do not specify what rates of erosion or deposition are necessary to meet (or not meet) the desired condition, however. Other metrics for assessing cultural resource condition include the presence of other impacts that affect National Register eligibility of sites (such as evidence of artifact collecting and deliberate vandalism). These latter impacts are not necessarily dam-related, however, and therefore would not be a focus of the future monitoring program being proposed by GCMRC. However, by combining the data that will be collected through the currently proposed project, along with other data that is being routinely collected by NPS to meet their Section 110 obligations and Section 106 obligations for other management purposes such the 2005 Colorado River Management Plan, plus monitoring data that is currently being collected by tribal stakeholders, it is possible to achieve multiple related objectives for monitoring cultural resource condition in the CRe.

The process of developing a new Long Term Experimental and Management Plan (LTEMP) to guide future operations of Glen Canyon Dam has highlighted the need for additional monitoring data that can help us better understand how dam-controlled flows affect cultural resource condition. Completion of the LTEMP may also introduce additional needs for monitoring in the future. While those additional monitoring needs are currently unknown, the monitoring plan that is proposed for development as part of Project Element 4.2 will be designed, at a minimum, to track the effects to cultural resources of whatever preferred alternative flow regime is ultimately selected.

C.3. Key Monitoring and Research Questions Addressed in this project

In element 4.1., the primary question that we will ask is: (1) How do the contemporary location and size of active and inactive aeolian sand deposits vary spatially throughout the river corridor as a function of, and in proximity to, controls that we have identified or hypothesized to be important? We hypothesize that important controls include:

- Upwind sand bars subject to scour and fill during HFEs
- Other sediment sources including deposits in tributary mouths, bare sediment surfaces on terrace treads and risers, campsites, and other high user impact areas
- Vegetation (either thick vegetation barriers that occur between fluvial sand bars and upland areas or cover of formerly open sand [source] areas)
- Topographic barriers including rock outcrops, debris fans, and tributary channels, and terrace risers

The second question that we will ask is how have location and size of active and inactive upland sand units varied temporally in the contemporary period of restricted power plant operation with controlled floods? This work will consider temporal changes relative to the hypothesized important controls presented above and employ interpretation of digital imagery acquired by overflights since 2002. We propose to test the following hypotheses:

- The distribution of aeolian sand has varied as a function of vegetation changes, and episodes of decreased potential for aeolian activity are evident in response to vegetation expansion at low elevations and increased potential for aeolian activity are evident in response to vegetation decreases (“drought pruning”) at high elevations

A third question we will consider is how has the presence of active and inactive aeolian sand varied within archaeological sites over longer-term pre- to post-dam time periods? Building on earlier work (Draut and Rubin, 2008) that found limited utility of the analog aerial photograph record for identifying trends in aeolian sand cover but recommended using oblique historical photographs for this purpose, this work will consider temporal changes in historical oblique photos and will test the following hypotheses:

- Cultural sites currently situated in inactive aeolian areas (areas that no longer receive aeolian sand inputs from upwind source areas) have more biologic crust cover and/or more vegetation cover today than in the past, and
- Cultural sites currently situated in inactive aeolian areas have more and/or larger gullies than in the past.

The fourth question that we will ask is: How are the processes and controls that govern aeolian-fluvial-hillslope connectivity impacted by the different effects that river regulation has on rivers? Answering this last question will involve a comparison of findings related to questions 1-3 asked in Grand Canyon with observations in Desolation and Gray Canyons of the Green River; we will specifically investigate whether, in the Desolation-Gray Canyon system with greater fluvial sediment supply and larger annual spring floods, there exists a greater proportion of active aeolian sand in upland sediment deposits than occurs in Grand Canyon. We are seeking non-GCDAMP funding for this last sub-element.

In element 4.2., we propose to draft and implement a monitoring plan that is designed to identify whether, and how much, HFE sand is transported by wind to a representative sample of archaeological sites, and then to measure the effect that wind transported sand has on site surface condition and site stability (i.e., the degree to which these processes mitigate effects from precipitation-induced gully erosion and other surface impacts). Review, approval, and implementation of the monitoring plan will require that BOR, NPS, and the tribes work very closely with GCMRC to come to agreement about the full scope and specific objectives of the monitoring program. In addition to satisfying BOR's Section 106 compliance responsibilities and to meeting legal requirements of GCPA for monitoring how changes in dam operations affect resource condition, the proposed monitoring program will be designed to test the following hypotheses:

- Cultural sites where adjacent, upwind fluvial sediment deposits form by high flow events, and that have unimpeded aeolian sand transport from the flood deposit toward the archaeological site (i.e., type 1), show less erosional surface change than sites of the other classification types (types 2-4) where either lack of sediment sources, presence of transport barriers, or both are potentially limiting factors, and where other factors (weather conditions, drainage catchment size) are approximately equivalent.
- Cultural sites where transport barriers are present, but fluvial source of aeolian sand is also present (i.e., type 2), show less erosional surface change than sites with no current fluvial source of aeolian sand (type 3 or 4).

Since approximately 30 sites within the Grand Canyon portion of the river corridor have received erosion control treatments (check dams) in the past (Leap and others, 2000), we also plan to further explore the efficacy of check dam treatments as a mitigation measure by evaluating potential differences in erosion condition between treated and untreated sites. While acknowledging that we might be limited logistically in our ability to sample a large number of sites with check dam treatments and untreated control sites, if sample sizes allow, we would propose to test the following two hypotheses:

- Cultural sites with check dams show less evidence of gully erosion than sites without check dams, regardless of whether or not they are situated downwind of open sand areas (e.g., among all archaeological site classes), and
- Cultural sites with check dams that are situated downwind of open sand source areas (i.e., type 1 and type 2 sites) show less evidence of gully erosion than sites with check dams that are not situated downwind of open sand source areas (i.e., type 3 and 4 sites).

D. Proposed Work

D.1. Project Elements

Project Element 4.1. Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales

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Helen Fairley, Research Specialist, USGS, GCMRC
Joshua Caster, Geographer, USGS, GCMRC

The primary objective of Project Element 4.1 is to explain how connectivity along the fluvial-aeolian-hillslope continuum varies spatially throughout the river corridor and to determine if this connectivity has changed during the recent decades of restricted power plant operation and the occurrence of controlled floods. As noted previously, we define connectivity (Merriam, 1984) as the "degree to which a landscape facilitates or impedes movement among resource patches" (Taylor and others, 1993). This project element includes three sub-elements that examine connectivity by focusing on the potential for movement of sand by wind from active channel sandbars to higher elevation sand landscapes. In the context of landscape connectivity, vegetation and topography have the potential to decrease the distance that sand can be transported, by decreasing the length of the connected pathway between source (e.g. sandbar) and sink (MFS sandscape) (Okin and others, 2009). The sub-elements are designed to examine the nature of connectivity between sand in the active channel of the Colorado River and higher elevation sand patches and to examine the factors that control these redistribution processes at different spatial and temporal scales. The first sub-element, examines landscape-scale spatial variability using a combination of remote sensing and GIS analyses of existing digital imagery and topography data that span the entire river corridor to test hypotheses developed during the FY 13–14 work-cycle about what environmental factors related to river operations control the location and size of aeolian sand deposits and whether or not these deposits contribute to the stability of archaeological sites. The second project sub-element will extend the first analysis farther back in time by conducting visual interpretation of historical oblique photos to assess whether hypothesized changes due to dam operations are supported by photographic evidence. The third project sub-element will investigate how the processes and controls that govern connectivity are impacted by the effects of river regulation on sediment supply. This last sub-element will contrast observations of aeolian sand distribution in Grand Canyon with other, analogous river systems, specifically Desolation and Gray Canyons of the Green River. The sub-elements are each described in further detail below.

In the first sub-element, we will conduct landscape-scale, remote sensing and GIS analyses of existing digital imagery and topography as well as geospatial databases developed and previously reported on for work conducted in the FY13–14 work plan (Sankey and Draut, 2014; East, 2014). We will spatially analyze the relative importance of the hypothesized controls independently for each date of "corridor-wide" digital imagery and topography that we have (e.g., 2002, 2009, and 2013). Methodological steps will be to first expand the aeolian sand map completed for the FY13–14 work plan to include the greater river corridor using image classification techniques and the existing maps as training data to identify river-derived upland sand (above 45,000 ft^3/s) that is active or inactive with respect to aeolian transport. In defining areas that are 'active' with respect to aeolian sediment transport, we assume that sand deposits are active where there is open sand area lacking vegetation, biologic soil crust, or matter other than sand; these are places where sediment forms wind-rippled surfaces and, locally, dune slipfaces at the angle of repose, thus meeting the criteria for 'active aeolian sand' defined by Lancaster (1994). We will next quantify relationships of the spatial proximity of aeolian sand units and their areal dimensions to the location and dimensions of adjacent and upwind fluvial sand (sandbar) deposits. We will similarly quantify relationships of aeolian sand units to alternative sediment sources that are adjacent and upwind, including exposed terrace scarps, tributary mouths, and open campsite areas. Work completed in the FY13–14 work plan described the role, in many locations, of riparian vegetation that produces a barrier to the inland and upslope transport of fluvially-sourced aeolian sand (East, 2014). Previous work also quantified the long-term trends of: (1) riparian vegetation that has consistently increased at lower elevations and encroached towards increasingly lower elevations in response to decreased flood magnitude and duration; (2) xeric (upland) vegetation that has exhibited increases and decreases at higher elevations in response to regional climate and specifically episodes of drought (Sankey and others, in review). Therefore, an important step will also be to examine how the presence, dimensions, and long-term stability of vegetation located between aeolian sand deposits and active channel sandbars, or formerly open sand areas, are related to the distribution and size of contemporary mapped aeolian sand deposits. Finally, we will quantify temporal changes in area and dimensions of aeolian sand units and attempt to explain changes as a function of variability in fluvial sand sources, alternative fine-sediment sources, and transport barriers. We will conduct the change analysis for the decadal time period between 2002 and 2013 for which high resolution digital imagery are available. We propose to statistically test the independent and interacting effects of the hypothesized explanatory variables for the response of aeolian sand unit area and change. Statistical tests may employ mixed model analysis with hypothetical effects (predictor variables) that could include, for example: distance and direction to fluvial sand; area of fluvial sand; distance, direction to, and area of vegetation barrier; stage-elevation of aeolian sand; relief or elevation difference between aeolian and fluvial sand; distance and direction to alternative sediment sources or topographic barriers such as camp sites or tributary channels, respectively; inferred or measured wind direction (including predominant, in addition to secondary or less common, wind directions where such information are available); as well as additional and potentially random effects such as geomorphic reach or distance from Glen Canyon Dam. The work in the first sub-element will be led by Joel Sankey with collaboration from Amy East and Joshua Caster.

In the second sub-element, we will extend the analysis back farther in time, to ascertain the degree to which environmental conditions at or near cultural sites have changed during the past > 50 years by comparing conditions in areas that appear to have functioned differently as aeolian landscapes in the past compared to current conditions. This work will be completed using qualitative visual comparisons of historical oblique imagery and current surface conditions.

Although the exact number of images that will be analyzed is currently unknown, we anticipate that several hundred historical images (>600) will be examined, of which perhaps 150-200 will contain information directly relevant to this analysis. Methods will include visual evaluations of area and cover of bare sand, soil crust, and vegetation. Images capturing cultural sites and aeolian sand source areas by photographers such as Stanton (1890), Birdseye (1923), Schwartz (1965), Euler (1960s), Shoemaker (1969), and Webb and others, (1990, 2010) will be the focus of the analysis. Historical photographs and recent imagery will be carefully examined and qualitatively assessed in terms of whether the imagery shows more or less biologic crust cover, vegetation cover, surface inflation or deflation, and other evidence of erosion or surface stability within specific areas designated as cultural sites and also within the areas that appear to have served as aeolian source areas to cultural sites (Figure 3). Changes in vegetation composition, density, biocrust cover, and evidence of surface deposition or erosion will be assigned to ranked categories reflecting “no apparent change”, “minimal change”, and “significant change”. We also propose to experimentally apply some automated techniques to digitized imagery to further quantify the changes in the amount of lateral vegetation cover evident in the photos. The current state of cultural sites and aeolian sand areas will be similarly assessed based on recent site photos as well as recent site descriptions (e.g., from site investigation work completed in 2013 and 2014). An important outcome of this analysis will be an estimate of the proportion of previously classified cultural sites for which the potential influence of aeolian sand inputs has changed with time, as reflected in changes in aeolian-sand-dependent environmental characteristics such as vegetation and biologic crusts. The work in the second sub-element will be led by Helen Fairley with collaboration from Joel Sankey, Amy East, and Joshua Caster.

In the third sub-element, we will investigate how the processes and controls that govern connectivity are impacted by the different effects of river regulation on sediment supply. This work will contrast observations in Grand Canyon with those in Desolation and Gray Canyons of the Green River, Utah. There, previous mapping has shown that numerous large aeolian deposits exist (Elliott, 2002) that are likely sourced from fluvial sandbars. In that system with greater fluvial sand supply and a flow regime that more closely resembles natural flows, we aim to map active and inactive sand deposits and to map the distribution of gullies. We will evaluate whether there is widespread evidence of gully annealing. This will also complement comparative work done in the Colorado River corridor through Cataract Canyon (Draut, 2012), but using a canyon where aeolian dunes are a more common feature of upland river-corridor morphology. The work in the third sub-element will be led by Amy East, conducted by an M.S. student at Utah State University supervised by J.C. Schmidt, with collaboration from Joel Sankey.

Figure 3. (Top) Stanton photograph of the Fossil area, looking downstream, February, 1890, Center photo: 1990. Bottom photo: May, 2014. In all three photos, the biologic composition (small and sparse arrowweed shrubs, bunch grasses, and lack of biocrust) is indicative of an active aeolian landscape, but note that the density and also pedestaling of some plants appears to have increased through time. Note also that there appears to be a greater exposure of rocks and deepening of swales in the sand dune surface in 2014 relative to the earlier photos. The arrow in the 2014 photo points towards a gully that formed in 2007 and is the focus of monitoring with repeat lidar surveys by Collins and others, (2012).

Project Element 4.2. Monitoring of cultural sites in Grand and Glen Canyons

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Joshua Caster, Geographer, USGS, GCMRC

The primary objectives of Project Element 4.2. are to 1) draft (in 2015) and 2) implement (in 2016 and 2017) a monitoring plan that meets requirements for monitoring effects of dam operations to cultural resources relative to the requirements of the Grand Canyon Protection Act and the terms of a new Programmatic Agreement currently being developed to achieve BOR's Section 106 compliance under the National Historic Preservation Act for the Long Term Experimental and Management Plan (LTEMP). At a minimum, the monitoring plan will be designed to identify whether, and how much, HFE sand is transported by wind to a representative sample of archaeological sites and to measure the effect of the wind-transported sand on site surface condition and site stability (i.e., the degree to which this mitigates effects from gully erosion and other surface impacts). Year 1 of the project will focus on drafting, reviewing, revising, and pursuing approval for the monitoring plan. Years 2 and 3 of the project will focus on implementing the monitoring plan. The draft plan will make a recommendation of the sample of archaeological sites that should be monitored, but stakeholders (presumably including the BOR, NPS, and tribes) will need to work very closely with GCMRC in year 1 of the project to come to agreement about the full scope and specific objectives of the monitoring program.

The BOR has explicitly recommended that the draft monitoring plan consider 22 points (M. Barger, email communication, May 19 2014, to J. Sankey). The NPS Grand Canyon Cultural Resource Program has also made explicit recommendations that the draft monitoring plan consider several points that include specific responses to some of the points presented by BOR (J. Balsom, email communication, July 7, 2014, to J. Schmidt, H. Fairley, G. Knowles). GCMRC will evaluate these recommendations in the course of drafting the plan as well as any additional recommendations provided by other stakeholders (note that in the following list, BOR recommendations are in plain text and *NPS comments are quoted in italics*):

1. Focus on sites that would benefit from HFE sand (types 1 and 2a, maybe 2b and 2c); "*We believe a full understanding of effects is necessary properly manage and mitigate adverse effects from dam operation, not just those that have beneficial effects. Reports by Sankey and East (2014) and East (2014) suggests that deposition and erosion can change through time, even at Type 1 sites."*
2. For those sites identified in #1, describe a method to determine which sites could receive enough sand to make a difference e.g. the HFE sand bar is large enough, the vegetation barrier is not too dense or the topographic barrier is not too large; "*We are not sure this direction is practicable as written. Does the comment really mean, describe a method to determine which sites could receive enough sand to stabilize them in-situ. Determine what HFE sand bar size is large enough, what density of vegetation is not too dense, and what topographic barrier is not too high to facilitate movement of sand to archaeological sites at a volume that will stabilize them in-situ. Reports by Sankey and East (2014) and East (2014) suggests that deposition and erosion can change through time, even at Type*

1 sites and we need to recognize that "type" may change over time given changing field conditions."

3. Define how much sand is needed to benefit a site that is eroding (this may be part of the methodology); "*We believe the answer to this question is going to be different for every site because it will relate to site type and features present, local topography and weather."*
4. Include criteria to determine where to focus the monitoring effort on such sites (gullies?); "*We believe monitoring activities have to look at an archaeological site within the landscape area where it exists. Tribes do not think of archaeological sites as only the physical manifestations of the past but the areas within which the sites are located. Perhaps something else is intended by the comment.*"
5. Include the number of sites and schedule/interval of monitoring events that would be statistically significant; "*We may be misunderstanding the context of this statement. We know what the number of sites present in the APE. The sample should be based on geomorphic context and the potential for indirect effects (both adverse and beneficial)*"
6. State criteria to be used in the evaluation of effectiveness that the HFE sand is making a difference for site erosion/stability; "*We think this statement may mean "State how you will quantify beneficial effects from HFE sand in making sites more stable. State how you will quantify adverse effects from HFE sand and site erosion.""*
7. Include a form used for any monitoring;
8. Define qualifications of the monitors;
9. State criteria to determine if covering the site with HFE sand would be an adverse effect by changing the site's setting;
10. State criteria to determine any other negative (adverse) effects from HFE sand on or across sites; "*We believe these (BOR points 9 and 10) are complex questions that can't be answered without tribal involvement and SHPO concurrence. We think it will depend on the type of site and how that site continues to be used by the traditionally associated tribes of the Grand Canyon (or Glen Canyon). The question really needs to address integrity of setting; the Colorado River setting has not changed, nor has the location of the archaeological sites. Evaluation of the aspects of integrity was performed a number of years ago and it might be worthwhile to incorporate previous evaluations into the component suggested in this project element.*"
11. Include strategies to re-evaluate sites to see if their type has changed; include strategies for removing sites from monitoring if HFE sand is either 1) not reaching the site or 2) not effective for stabilizing erosion;
12. Precisely define all monitoring attributes that will be used (e.g. how will you use lidar?); "*We think the word "attributes" is referring to "methods" if the discussion is about field activities. If the discussion refers to analysis then the word for "attributes" might be "data.""*
13. For monitoring not using lidar, include what will be measured;
14. Since geomorphic conditions can vary from time to time based on sand availability and weather conditions, state how temporal variations of this type will be incorporated into the assessment of effectiveness;
15. State the criteria by which plant cover will be evaluated in relation to sand transport to and across the site (this could include how evaluate cryptogamic crust);

16. How you will determine if the archaeological assemblage is in situ or has been lowered to an erosional surface (mixing of components); "*We are not sure about what is intended here. In-situ deposits can be mixed chronologically as a result of site use from multiple occupations. Sheetwash would be evidence of movement. In any case archaeological sites are recorded in situ and monitoring information would indicate if creep and sheetwash are currently moving artifacts or features in the site context. We can't think of any archaeological sites that have been moved and whole redeposited elsewhere. If it were to occur, it would be obvious in the geomorphic context of the site. There would be no uniformity or human agency in the archeological deposits present in such cases. We are not sure this statement is relevant.*"
17. Define the criteria for active vs. inactive sand;
18. Where weather station is used, describe what data is collected and how it will be analyzed;
19. Where remote cameras will be used, describe what data is collected and how it will be analyzed;
20. Describe how new sites (discoveries) will be addressed and assigned a type;
21. Include a method to report findings to the PA signatories; and
22. The GCMRC's geoarchaeologist should be instrumental in developing this plan.

Two additional comments from the NPS Grand Canyon Cultural Resource Program are:

- *It is imperative to link monitoring activities to mitigation actions. The key purpose of the monitoring program, in our view, is to track resource condition, identify disturbance mechanisms, implement strategies, i.e., mitigations, to reduce adverse effects resulting from disturbance mechanisms, and evaluate the efficacy of treatment actions. There may be a tendency to describe research as monitoring.*
- *Drafting a monitoring plan will definitely require close cooperation to negotiate issues related to requirements, management recommendations, and agency mission for example. We feel we need more information to develop the site sample, the time frame for monitoring sites, the variables that will be observed/collected and other specifics. It is imperative that a monitoring program be easily replicated and provide information to allow management decisions and treatments by the management entity.*

Development of the monitoring plan in 2015 will clearly require that we work closely with all stakeholders including the tribes, NPS, and BOR – and also that stakeholders work closely with each other – to come to agreement on an approach that can collectively address the science recommendations of each group. While the monitoring protocol that is ultimately adopted will be contingent on consultation and review from all stakeholders, we believe it is logical to propose to design the monitoring plan in the context of the 5-class archaeological site classification system developed and applied in 2013 and 2014 (East, 2014). The classification provides useful, site-specific expectations of landscape response to dam operations and controlled floods, and potentially will allow us to make inference from detailed monitoring and measurements conducted at a smaller sample of site to the larger population of sites in the CRe. While recent monitoring efforts by GCMRC have focused on the use of lidar to measure topographic changes, in drafting the monitoring plan we will also consider the use of other monitoring methods and tools. In particular, we will consider protocols and tools that might be used by NPS and/or tribes on river trips not led by GCMRC personnel. This might include, for example, keeping track of presence of sandbars upwind of archaeological sites with repeat oblique photography, tracking changes in the lateral cover and porosity of vegetation barriers with repeat oblique photography, measuring area of active aeolian sand at sites and between HFE deposits and archaeological sites, measuring the cover and stature and spacing of vegetation at sites or between HFE deposits and sites, and documenting wind directions near fluvial sandbars from sand shadows, ripples, and dune slip faces.

In drafting the monitoring plan, we will consider the recent synthesis of 5 years of monitoring surface-elevation changes from ground-based lidar at archaeological sites in Grand Canyon (Collins and others, in review) in the context of the site classification system (Figures 1 and 2). Figure 1 indicates that variability exists among sites in the degree to which they are linked to modern river processes and specifically their relative potential to receive aeolian influx of river-derived sand. Figure 2 shows the mean response with time of runoff and aeolian surface change for different classes of archaeological sites measured with lidar during site investigations between 2006 and 2010. The large uncertainties (shown by bars that are the standard error of the mean for n sites in Figure 2) demonstrate the inherent limitations associated with the small sample sizes of the present monitoring program (# of sites per class). For example, the large amount of erosion shown for Type 1 sites reflects the presence of one recently formed and exceptionally large gully at a single site (Collins and others, 2012; in review.) Therefore, while the existing lidar monitoring data provide useful information about landscape response to dam operations and controlled floods, additional data (i.e., additional sites but also additional repeat visits of previously measured sites) are required to tighten the uncertainty about the mean responses and identify any observed differences that are statistically significant.

Summary of existing lidar monitoring data indicate that type 1 and 2 sites – which have upwind sources of flood-supplied sand but differ in terms of the existence of transport barriers – might exhibit some of the largest surface elevation changes attributed to aeolian processes (Figure 2); an expected result based on the site class definitions. However, fewer than half of these type 1 (2 of 5 sites) and type 2 (2 of 4 sites) sites exhibited measureable aeolian deposition during the time period of analysis. Moreover, a majority of all sites (8 of 13 total sites), encompassing a variety of classes, had measurable aeolian erosion. Therefore, our current interpretation of the site-specific surface elevation changes in the context of the archaeological site classification suggests that most sites of all classes are likely not transport limited with respect to aeolian processes (i.e., wind energy is often sufficient for transport); however, even the most favorably positioned sites (type 1 and type 2) with respect to fluvial sources of aeolian sand can still be lacking in either sediment source and/or possibly the right temporal and spatial interaction of wind and sediment availability to cause net long-term deposition and improve the chance of archaeological-site preservation in place. The site-specific surface-elevation lidar monitoring employed for these analyses was conducted with repeat site measurements on the order of once every 1-3 years (Collins and others, in review); field campaigns were strategically designed such that every site under consideration was not necessarily measured in a single campaign or year, but a longer term record of change was still amassed for a maximum number of sites (Table 1). In the context of the archaeological site classification system, change detection results by volume, mechanism and type (runoff erosion, aeolian erosion, runoff deposition, aeolian deposition) will have been derived by the end of 2014 for various intervals between 2006 and 2014 at five type 1 sites, five type 2 sites, four type 3 sites, and three type 4 sites (Table 1).

Table 1. Summary of measurement intervals for lidar change detection by archaeological site

			Lidar Change Intervals						
	Site Jurisdiction	Class	5/2006-5/2007	5/2007-9/2007	9/2007-4/2010	9/2007-9/2010	4/2010-9/2010	11/2012-11/2013	5/2013-5/2014
1	GRCA	1					x		x
2	GRCA	1					x		x
3	GRCA	1				x			x
4	GRCA	1	x	x		x			x
5	GRCA	1	x	x		x			x
6	GRCA	2a	x	x		x			
7	GRCA	2a		x		x			
8	GRCA	2b	x	x	x				
9	GRCA	2b	x	x					
10	GLCA	3						x	
11	GLCA	3						x	
12	GLCA	3						x	
13	GLCA	3						x	
14	GRCA	3	x	x					
15	GRCA	4	x	x			x		
16	GRCA	4	x	x	x		x		
17	GRCA	4	x	x	x		x		

In drafting the monitoring plan, we will consider whether the continuation of detailed characterization of topographic changes with lidar, such as conducted by Collins and others (in review) is necessary for monitoring whether and how much HFE sand is transported by wind to archaeological sites, and to measure the effect that wind transported sand has on site surface condition and site stability. We might, for example, propose to incorporate additional sites to the set measured by Collins and others, (in review) and in surveys completed in 2013 and 2014, such that we maintain a meaningful number of sites (i.e., n = 3 to 5 clearly presents limitations for evaluating the central tendency and uncertainty among classes of sites; even a slightly larger sample size might be extremely useful for identifying the variety of landscape process trends) of each of the classification types 1, 2 (a+b), 3 and 4. With the combination of the existing and new terrestrial lidar survey time series data in addition to other measurements that may be made as part of the new monitoring protocol, we will be positioned to answer the following questions:

1. Do sites where adjacent, upwind fluvial sediment deposits form by high flow events, and unimpeded aeolian sand transport from the flood deposit toward the archaeological site (i.e., type 1), show different types of surface change and less erosion by gullies and overland flow than sites of the other classification types where either lack of sediment source, presence of transport barriers, or both are potentially limiting factors?
2. Do sites where transport barriers are present, but fluvial source of aeolian sand is also present (i.e., type 2), show different types of surface change and less erosion by gullies and overland flow than sites without a fluvial source of aeolian sand (type 3 or 4)?

Check dams have been installed at several sites by the NPS and, depending on the recommendations of stakeholders, could also be considered in addition to aeolian sand influx as a possible interacting control on erosion and surface elevation changes within archaeological sites. Sites of any classification type where check-dam-type erosion control treatments have been applied might be expected to benefit from interacting effects of dam operations and high flow events with the erosion control treatments. It might not be logistically feasible to monitor the large number of sites from each class that might be required to test for significant effects and interactions of site class and check dam treatments. However, in drafting the monitoring plan, we will consider the potential of using the combination of the existing and new terrestrial lidar survey time series data to ask, "Do sites of any classification type that have check dams exhibit surface elevation changes and types of change that appear to be anomalous relative to those without check dams?"

Vegetation barriers are perceived as the most temporally transient obstacle to aeolian influx for sites that have a modern fluvial source of aeolian sand. Defoliation of tamarisk owing to the recent spread of the tamarisk beetle is one of the only contemporary environmental factors that might increase the potential for aeolian sand transport through vegetation barriers. Potential future vegetation reduction treatments might also be useful for promoting aeolian sand transport from fluvial sources to upslope cultural sites. In drafting the monitoring plan, we will consider the potential for using existing airborne lidar data (from previous high density airborne lidar acquired in 2013–2014 in GLCA; Collins and others, in press) in addition to existing or new terrestrial lidar site surveys as appropriate, to evaluate effects of changes in porosity, stature, and spacing of vegetation barriers, such as might occur with tamarisk defoliation or potential treatments that would reduce or remove the barrier of vegetation within units of active aeolian sand and between fluvial sources of sand and higher elevation cultural sites. We could for example, examine natural gradients of vegetation cover and porosity, as well as manipulate the lidar datasets to represent different levels of cover and porosity – e.g., that could be characteristic of different intensities of vegetation treatments or defoliation – and use an aeolian transport model to estimate potential sediment fluxes for the different vegetation treatment scenarios. The methodology for this work has been previously tested and published by Sankey and others, (2013) for different levels of mesquite encroachment in a Sonoran desert vegetation community and the transport model is presented in Okin (2008) and validated in Li and others, (2013).

Ground based lidar has proven to be a useful and efficient tool for tracking fine-scale changes of upland environments associated with cultural sites in Glen, Marble and Grand Canyons, and the technology also holds promise for future interdisciplinary physical science and aquatic ecology work at GCMRC focused on mapping terrestrial settings and near-shore environments. Although in past years GCMRC has relied on personnel and equipment from other USGS centers to perform lidar surveys, for future monitoring that uses lidar, we intend to rely on "in-house" terrestrial lidar capacity at GCMRC. This would require the purchase of a lidar scanner and hiring of a survey/scanner technician prior to implementing the monitoring plan. River trips in year 2 and year 3 would likely be conducted to collect lidar topography using protocols developed and tested in the FY13–14 and prior GCMRC work plans. Pending NPS approval, the currently deployed automated weather stations and stationary cameras (installed in FY13) would continue to collect data on local weather conditions at 24.5 mile, 70 mile, 126 mile, and 223 mile (all type 1 sites in the recent classification) to refine our current understanding of how local weather events contribute to the erosion and/or deposition measured at this sample of type 1 sites; these data are useful for attributing site-specific surface elevation changes to meteorological events. The weather stations that are currently deployed in GRCA are permitted to collect data through April 30, 2015, and we will discuss with the NPS extension of the permit through the duration of this project (December, 2017).

D.2. Personnel and Collaborations

This project builds upon several past research efforts, including very recent work completed in 2013 and 2014 by Sankey and Draut (2014), Collins and others, (in review, in press), and East (2014). It builds upon the previous work of Draut and Rubin (2006, 2008), Draut and others, (2005, 2009a, 2009b, 2010a, 2010b), Draut (2011, 2012), Pederson and others, (2003, 2006) O'Brien and Pederson (2009a, 2009b), Damp and others, (2007), Fairley and others, (2007; Fairley and Sondossi 2010) and Collins and others, (2008, 2009, 2012). Specifically, it directly builds upon the Phase I work of the Cultural Monitoring Research and Development Project by applying the knowledge gained through that effort (Collins and others, 2008, 2009, 2012, in press); Draut and others, 2009a, 2009b, 2010a, 2010b; O'Brien and Pederson 2009a, 2009b) to track and quantify dam-related topographic changes (i.e., amounts and rates of erosion and deposition from fluvial sand sources) occurring at cultural sites throughout the CRe.

This study complements Grand Canyon National Park's CRMP monitoring program. Monitoring protocols for assessing impacts of human visitation at archaeological sites have been developed independently by GRCA staff to serve the monitoring needs of the NPS for evaluating effects of visitation at cultural sites (Dierker and Brennan, 2011), and tribal monitoring programs also collect information related to visitor use impacts. These sources of data will be drawn upon in the analysis of the results of this project specifically to determine whether measured surface changes correlate with NPS's documentation of visitor use levels, as reflected in monitored visitor use impacts. The quantitative approaches for monitoring change in archaeological site condition developed through the previous cultural monitoring R&D effort and proposed for implementation now as part of this project will supplement and enhance the qualitative, observational monitoring protocols and data developed by NPS for CRMP compliance and by the tribes who monitor resource conditions in Grand Canyon through the adaptive management program.

D.3. Deliverables

An annual report on the progress of the project with relevant results, maps and graphics will be prepared for each year of the project. For element 4.1, at least one journal article or professional USGS report will be prepared in FY17 for each sub-element. These publications are expected to address several of the themes of the proposed work, including:

- connectivity along the fluvial-aeolian-hillslope continuum in Grand Canyon;
- implications of river regulation, and variability in downstream responses of rivers to dams, for connectivity along the fluvial-aeolian-hillslope continuum;

- documenting changes in the size and location of aeolian sand dominated landscapes, as determined from the analysis of historical oblique photographs;
- evaluating potential effectiveness of management treatments for promoting aeolian redistribution of fluvially-sourced sand along the fluvial-aeolian-hillslope continuum, and mitigating erosion of cultural sites in Grand Canyon

For element 4.1, if funding is secured for the third sub-element that will contrast observations of aeolian sand distribution in Grand Canyon with other, analogous river systems, a thesis and journal publication will be produced from this work.

For element 4.2, the monitoring plan will be drafted in FY15, and a monitoring report will be completed in FY17 that reports on the results of monitoring implemented in FY16 and FY17.

E. Productivity from Past Work (during FY13–14)

E.1. Data Products

E.2. Completed Publications

Hereford, R., Bennett, G.E., and Fairley, H.C., 2014, Precipitation variability of the Grand Canyon region, 1893 through 2009, and its implications for studying effects of gullying of Holocene terraces and associated archeological sites in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 2014–1006, 23 p., http://dx.doi.org/10.3133/ofr20141006.

Sankey, J.B., Draut, A.E., 2014. Gully annealing by aeolian sediment: Field and remote-sensing investigation of aeolian-hillslope-fluvial interactions, Colorado River corridor, Arizona, USA. *Geomorphology* 220, 68-80, doi: 10.1016/j.geomorph.2014.05.028

Collins, B.D., Corbett, S.C., Sankey, J.B., Fairley, H.C., in press. High resolution topography and geomorphology of select archaeological sites in Glen Canyon National Recreation Area, AZ. US Geological Survey, Scientific Investigations Report 2014-XXXX

Dealy, T., East, A.E., and Fairley, H.C., 2014. 2010 weather and aeolian sand-transport data from the Colorado River corridor, Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 2014-1135, 90 p., http://dx.doi.org/10.3133/ofr20141135

E.3. Publications in progress

Collins, B.D., Bedford, D., Corbett, S.C., Cronkite-Ratcliff, C, and Fairley, H.C., in review. Meteorologic and anthropogenic effects on archeological site change in Grand Canyon, Arizona: fluvial-aeolian interactions within a dam-controlled river corridor. (Submitted to Journal of Geophysical Research: Earth Surface)

Caster, J., Dealy, T., Andrews, T., Fairley, H., East, A., Collins, B., Sankey, J, Bedford, D. Meteorological data for select sites along the Colorado River Corridor, Arizona, 2011-2013, US Geological Survey, Data Series Report 2014-XXXX, in preparation.

E.4. Presentations at GCDAMP meetings

Sankey, J.B., Draut, A.E., Fairley H., Collins B., Bedford, D., 2014, Gully annealing by aeolian sediment: Field and remote-sensing investigation in Glen, Marble, and Grand Canyons. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ

Collins, B., Corbett, S., Bedford, D., Fairley, H., Sankey, J., 2014. Quantifying archaeological site erosion in Glen Canyon National Recreation Area and Grand Canyon National Park to assist sand resource management and operations of Glen Canyon Dam. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ

Collins, B., Corbett, S., Bedford, D., Fairley, H., Sankey, J., 2014. Quantifying archaeological site erosion in Glen Canyon National Recreation Area and Grand Canyon National Park to assist sand resource management and operations of Glen Canyon Dam. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ (poster)

Collins, B., Corbett, S., Sankey, J., Fairley, H., 2014. High resolution topography and geomorphology of select archaeological sites in Glen Canyon National Recreation Area, Arizona. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ (poster)

Sankey, J.B., Draut, A.E., Fairley H.C., Collins B., Bedford, D., 2014, Gully annealing by aeolian sediment: Field and remote-sensing investigation in Glen, Marble, and Grand Canyons. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ (poster)

Fairley, H.C., Draut, A.E., Sankey, J.B., Collins, B., Bedford, D., Corbett, S., 2014. Landscape-scale management implications of cultural resource studies. Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program, Jan. 29, 2014, Phoenix, AZ.

E.5. Presentations at professional meetings

Fairley, H.C., Collins, B., Draut, A.E., Corbett, S. and Bedford, D., 2014. Evaluating the Effects of Glen Canyon Dam on Downstream Archaeological Sites in Glen and Grand Canyons, Arizona. 78th annual meeting of the Society for American Archaeology, April 24, Austin, TX.

Sankey, J.B., Draut, A.E., 2013, Reconciling historical and contemporary evidence of aeolian-based, gully annealing processes in Glen, Marble, and Grand Canyon, USA. American Geophysical Union Fall Meeting, Dec 9-13, San Francisco, CA.

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Collins, B.D., Bedford, D., Corbett, S.C., Cronkite-Ratcliff, C, and Fairley, H.C., in review. Meteorologic and anthropogenic effects on archeological site change in Grand Canyon, Arizona: fluvial-aeolian interactions within a dam-controlled river corridor. (Submitted to Journal of Geophysical Research: Earth Surface)

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$197,800**	**$9,000**	**$10,000**	**$0**	**$0**	**$84,900**	**$33,900**	**$335,600**
		X					4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$107,200	$9,000	$2,500	$0	$0	$75,000	$18,600	$212,300
X	X						4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$90,600	$0	$7,500	$0	$0	$9,900	$15,300	$123,300
FY16																	
							4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$285,000**	**$14,000**	**$63,000**	**$30,000**	**$0**	**$87,300**	**$83,600**	**$562,900**
		X					4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$99,200	$10,000	$5,000	$0	$0	$77,100	$24,400	$215,700
X	X						4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$185,800	$4,000	$58,000	$30,000	$0	$10,200	$59,200	$347,200

Monitoring		Research																
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY17							
							4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$317,200**	**$14,000**	**$34,000**	**$30,000**	**$0**	**$87,300**	**$108,200**	**$590,700**
		X					4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$119,800	$10,000	$8,000	$0	$0	$77,100	$37,700	$252,600
X	X						4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$197,400	$4,000	$26,000	$30,000	$0	$10,200	$70,500	$338,100

Project 5. Foodbase Monitoring and Research

Initial Estimate: FY15: $521,200; FY16: $591,900; FY17: $596,700

GCDAMP Funding: FY15: $521,200; FY16: $550,500; FY17: $566,900

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B. Project Summary

The productivity of the aquatic foodbase, particularly invertebrates, fuels production and growth of fishes in the Colorado River. However, recent studies by Kennedy and collaborators have shown that the productivity of this foodbase is low. Further, the foodbase in Grand Canyon is dominated by only two groups of invertebrates: midges and blackflies, both of which are small-bodied, relatively low-quality prey. Larger, more nutritious aquatic insects such as mayflies, stoneflies, and caddisflies (hereafter, EPT), are virtually absent throughout Glen, Marble, and Grand Canyons. These conditions of low invertebrate productivity and the absence of high quality invertebrate prey have resulted in a fishery throughout Glen, Marble, and Grand Canyons that is food-limited, negatively affecting the abundance of native fishes such as humpback chub (*Gila cypha*), as well as the growth of recreationally-important non-native rainbow trout (*Oncorhynchus mykiss*). If the factors and stressors affecting this low foodbase productivity and diversity can be isolated, adaptive management experimentation intended to ameliorate these stressors, and benefit the productivity and diversity of the aquatic foodbase, could be considered.

In this proposal, we describe a multi-faceted approach to better understanding the conditions effecting the low productivity and diversity of the foodbase in the Colorado River, as well as an experiment to potentially improve these conditions. We focus principally on two methods: sampling emergent aquatic insect adults on land, and sampling aquatic invertebrate larvae in the drift. Sampling emergent insects allows for the observation of large-scale patterns in insect dynamics through time and over large spatial scales, such as throughout the entire Colorado River in Grand Canyon. In contrast, sampling invertebrate drift allows us to understand the fine-scale factors affecting invertebrate populations, particularly during a phase (drifting in the water column) in which these invertebrates are most available to fish. To a lesser extent, we also describe the continuation of a monitoring effort to estimate algae production in the Colorado River, which represents the base of the entire aquatic food web and the food resources available to these invertebrate populations.

Many of the studies we propose here are logical continuations of projects initiated in FY13–14, such as an expansion of the citizen science monitoring of emergent insects and the development of a more mechanistic understanding of the factors controlling invertebrate drift. In addition, we intend to synthesize published datasets to explore the factors affecting invertebrate productivity, diversity, and EPT abundance throughout tailwaters in the Intermountain West. We will couple this synthesis with natural history observations and lab studies of invertebrates in the Colorado River and adjacent ecosystems. The goal of those studies is to better understand how the specific insects present in the Colorado River and its tributaries in Glen, Marble, and Grand Canyons respond to environmental conditions such as altered temperature regimes and daily hydropeaking. We also propose to carry out insect emergence and drift studies in other Colorado River Basin tailwaters and in Cataract Canyon to better characterize aquatic foodbase conditions in reference ecosystems, and to determine whether the foodbase downstream of Glen Canyon is unique, or broadly similar to other river segments in the region. Finally, based on logic described below, we identify recruitment limitation of insects as a primary stressor limiting both invertebrate production and the colonization of EPT in the Colorado River in Glen, Marble, and Grand Canyons. Accordingly, we outline a flow experiment that could be implemented in FY15–17 involving weekend summer steady flows that may mitigate this recruitment limitation. If successful, this experiment would improve the short- and long-term productivity and diversity of the aquatic foodbase and, ultimately, the condition of fish populations and the stability of food webs in the Colorado River.

C. Background

C.1. Scientific Background

Productivity and Diversity of the Aquatic Foodbase

The primary focus of foodbase research at GCMRC over the past two decades has been on the broad-scale characterization of the aquatic foodbase in Glen, Marble, and Grand Canyons. The recent culmination of this research has been illuminating, particularly because of the strong links that were identified between flow management, the invertebrate prey base, and fish populations. Specifically, food web architecture and energy flow were quantified and it was shown that the growth and abundance of rainbow trout in Glen Canyon and native fishes in Grand Canyon are limited by the absence/scarcity of high quality invertebrate prey (Cross and others, 2013; Kennedy and others, 2013b). The foodbase is dominated by two aquatic insect taxa, midges and blackflies, and production of these taxa is low (Cross and others, 2013; Kennedy and others, 2013b). In fact, annual invertebrate production across four reaches of the Colorado River in Grand Canyon falls in the bottom 10th percentile of invertebrate production values for streams and rivers worldwide (Huryn and Wallace, 2000). This result is surprising because midges and blackflies can be among the most productive invertebrate taxa in streams and rivers. For example, four of the eight highest invertebrate production values ever measured for streams and rivers (production levels 100-1000 times higher than in Grand Canyon) were in streams where midges and blackflies were the dominant taxa in the assemblage (Huryn and Wallace, 2000).

Further, the tailwater synthesis GCMRC initiated in FY2013 revealed that it is actually a unique condition for a tailwater to support only two insect taxa; the invertebrate assemblage in the Glen Canyon tailwater supports fewer aquatic insects than any of the 58 other tailwaters in Dibble's tailwater synthesis database (Kennedy and others, 2014a; Dibble, USGS, unpublished data). This is significant, because low insect diversity likely contributes to food limitation of fishes in the River, as larger-bodied, higher-quality invertebrates in the mayfly, stonefly, and caddisfly groups ("EPT," from their collective Order names: Ephemeroptera, Plecoptera, and Trichoptera, respectively) are conspicuously absent (Cross and others, 2013; Kennedy and others, 2013b). Whereas midges and blackflies are known to be some of the most stress-tolerant groups of aquatic invertebrates, EPT taxa are actually used as bio-indicators of stream quality nationwide and internationally (Lenat, 1993). EPT taxa are useful bio-indicators on a global scale because: 1) EPT are universally present in streams and rivers, but they are sensitive to human perturbation and 2) they are universally important to fish populations. An important benefit of the EPT metric is that simply measuring EPT abundance or richness, and then relating it to other streams/rivers in the region, provides an integrated measure of food web structure and stream health (Lenat and Penrose, 1996; Barbour and others, 1999). The condition of zero EPT taxa in Glen Canyon, and only one EPT taxon (the micro-caddisfly, Hydroptilidae) at very low densities in Marble and Grand Canyons, would result in the Colorado River ecosystem being classified as "unhealthy," regardless of the specific reference condition used for comparison (Carlisle and others, 2013). Although some may argue whether invertebrates have value or importance in their own right, in practical terms, low aquatic insect diversity and simple food web architecture result in fish populations and food webs that are inherently unstable (Cross and others, 2013).

It is commonly accepted in aquatic ecology that flow and temperature alterations associated with river regulation can lead to invertebrate assemblages that are "unhealthy" (Bunn and Arthington, 2002). Specifically, regulation often leads to invertebrate assemblages that are dominated by non-insects such as worms, snails, and amphipod crustaceans like *Gammarus spp.*, while insect groups such as EPT taxa tend to decline in abundance (Vinson, 2001; Robinson, 2012). However, the extremely low EPT condition found in the Colorado River downstream of Glen Canyon Dam is unusual even relative to other regulated rivers in the region (Fig. 1). In contrast to the Glen Canyon Dam tailwater where no EPT are found, EPT taxa represent 24–35% of the invertebrate assemblage in five other large tailwaters in the Colorado River Basin.

One possible explanation for the low diversity of the aquatic foodbase in Glen, Marble, and Grand Canyons may be that the invertebrate assemblage has never been diverse, even before construction of Glen Canyon Dam. The physical template of the pre-dam Colorado River did have a dramatic disturbance regime with many distinctive characteristics that may have made life in the River difficult for aquatic invertebrates (Resh and others, 1988), including large snowmelt floods, extremely high suspended sediment concentrations, and low water clarity. However, the Green and Colorado Rivers located near or within Cataract Canyon, approximately 100 river miles upstream of Glen Canyon Dam, maintain similar characteristics to the pre-dam river, and the invertebrate assemblage of these reaches includes 16 genera of mayflies (Order Ephemeroptera), 7 genera of stoneflies (Order Plecoptera), and 7 genera of caddisflies (Order Trichoptera; Haden and others, 2003; Fig. 1). Tributaries in Grand Canyon also support a diverse invertebrate assemblage that includes many species of EPT (Oberlin and others, 1999; Whiting and others, 2014). It thus seems probable that EPT were extirpated from the mainstem Colorado River at some point in the past half century, and that some stressors exist that prevent these groups from recolonizing the river.

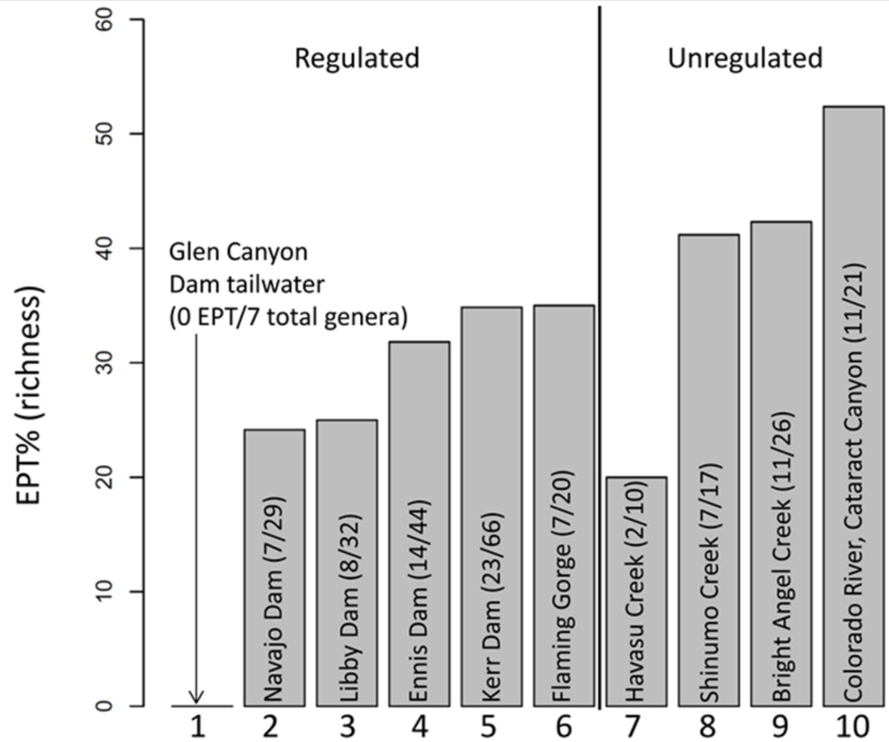

Figure 1. EPT% richness for six regulated rivers, including the Glen Canyon Dam tailwater (1–6), three Grand Canyon tributaries (7–9), and the Colorado River in Cataract Canyon. EPT% richness is the number of genera of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) relative to the total number of invertebrate genera in the assemblage. EPT values for regulated rivers (1–6) are derived from benthic invertebrate samples collected within 25 km downstream of their respective dam. Regulated rivers data are courtesy of Kim Dibble, USGS, and Grand Canyon tributary data are courtesy of Brian Healy, NPS. Cataract Canyon data are from Haden and others (2003).

Using midges and blackflies as surrogates for *all* aquatic insects, including EPT, it may be possible to identify specific, principal stressors affecting the aquatic foodbase in Glen, Marble, and Grand Canyons. For example, over the past two years river guides working in Marble and Grand Canyons have been serving as "citizen scientists" by setting out light traps at night and collecting the winged, terrestrial adult forms of aquatic insect larvae. These data show striking spatial and temporal patterns in midge and blackfly emergence that likely reflect similar variation in larval aquatic invertebrate densities within the River (Statzner and Resh, 1993). They can also be used as indicators of environmental stress, as the timing of emergence can be affected by environmental cues (Lytle, 2002). Analysis of the citizen science data in Grand Canyon is ongoing; however, preliminary data suggest that emergent insect dynamics may be affected by changes in the hydropeaking regime, the daily timing of high water at a given location, and monthly step changes in flow (Fig. 2).

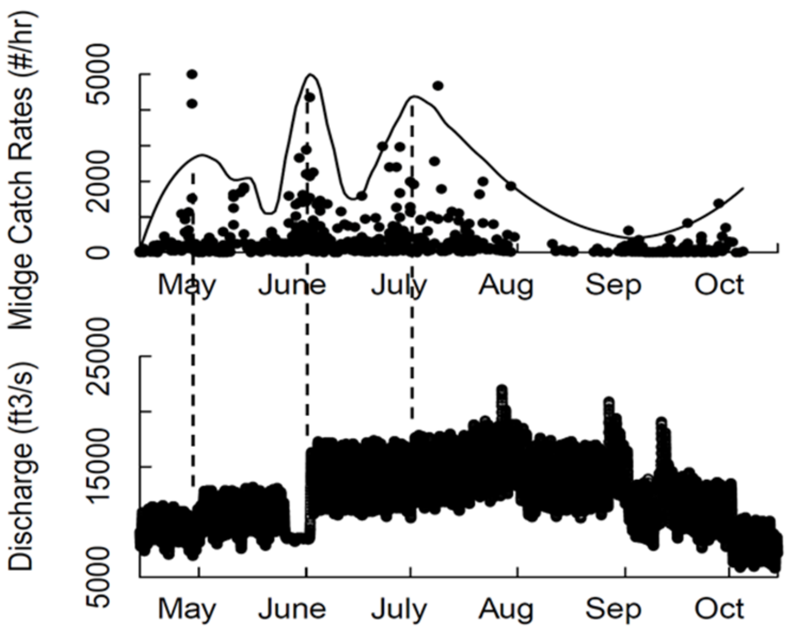

Figure 2. Midge catch rates and Colorado River discharge in summer 2013. Note midge emergence peaks at the end of the month, followed by steep declines coincident with stepped changes in flow.

If the specific stressors that prevent EPT from becoming re-established can be better identified, then the Glen Canyon Dam Adaptive Management Program could consider evaluating alternative policies that mitigate these stressors (see section C.4, below, for a proposed flow experiment). Re-establishment of EPT will improve the overall health of the River, and it will likely also increase the overall productivity of the foodbase. This is because, as bio-indicators, EPT are sentinels of environmental perturbation, meaning a decrease in the abundance, density, or richness of these taxa is generally mirrored by declines in other aquatic invertebrate groups. Midges and blackflies, as insects, have similar life histories to EPT taxa, but are less sensitive to environmental perturbation. The same stressors that are sufficient to prevent mayflies, stoneflies, and caddisflies from recolonizing the Colorado River may also be negatively affecting midge and blackfly populations, albeit to a lesser extent, thereby directly causing their low overall production. Therefore, even in the absence of successful re-colonization by EPT taxa, mitigation of the stressors that might be limiting aquatic insects in general could still have the beneficial effect of increasing the production of midges and blackflies present in the aquatic foodbase. Thus, adaptive management experimentation intended to improve the aquatic foodbase in Glen, Marble, and Grand Canyons should consider not only ways to improve the productivity of existing groups, but also approaches that will improve the overall diversity of the invertebrate assemblage as a whole.

Invertebrate Drift in Tailwaters

Over the past several years, GCMRC foodbase research has also been focused on measuring invertebrate drift, particularly in Glen Canyon. Invertebrate drift is a ubiquitous phenomenon in freshwaters, in which aquatic insects and other macroinvertebrates leave the channel bed and become entrained or caught in the water column. Unlike the broad-scale, system-wide patterns in the foodbase described above, measurement of invertebrate drift can allow the study of invertebrate population dynamics at spatial scales that are directly relevant to fish populations.

Quantifying invertebrate drift concentrations (#·m^{-3}), and the spatial and temporal variation in drift at this level of resolution is critical from a fisheries perspective, because these drifting invertebrates represent a key food resource for many fish species. Relevant to the Colorado River, the endangered humpback chub (*Gila cypha*) and recreationally-important non-native rainbow trout (*Oncorhynchus mykiss*) are both classified as "drift-feeding fishes," meaning that they rely on invertebrate drift as the key component of their foodbase.

In addition, drifting represents a key life stage for many aquatic invertebrates. Drift can be a behavioral response to avoid predation or to move away from unfavorable habitat. It can also be unintentional or "catastrophic" in nature, such as during floods when high water velocities shear invertebrates off the channel bed. Finally, for aquatic insects specifically, drift necessarily occurs during the transitional time between when insect larvae leave the channel bed and when they emerge out of the water as winged adults. Thus, measuring invertebrate drift concentrations provides data about the stability of aquatic invertebrate populations and the conditions underlying the entire aquatic food web.

Foodbase research has documented that aquatic invertebrate drift in Glen Canyon is controlled by a suite of factors, including benthic invertebrate density (Kennedy and others, 2014b) and physical variables such as discharge (Kennedy and others, 2014b), bed shear stress (the force of the water acting on bed sediment and biota), and distance from the dam (Muehlbauer and others, 2013; Fig. 3). These results have improved our general understanding of the conditions under which drift occurs; however, the specific mechanisms by which many of these variables actually affect invertebrate drift remain unclear. For instance, "catastrophic" drift (Anderson and Lehmkuhl, 1968) occurs when invertebrates are physically removed from the channel bed and a high proportion of the available invertebrates become entrained in the drift. If the conditions for initiating catastrophic drift persist for prolonged periods of time, benthic populations can be depleted, reducing the food base available to support fish over long time scales (i.e., months to years). Logically, such catastrophic drift may be initiated when one of three conditions is met (Gibbins and others, 2007a; b):

1. Shear stress is sufficient to entrain sand and "sand blast" invertebrates off the bed.
2. Shear stress is sufficient to physically remove invertebrates off the bed.
3. Very high shear stress mobilizes the cobble substrates on which invertebrates live.

Some data are available for small streams (<10 ft^3/s) in linking the initiation of catastrophic drift to specific shear stress and sediment grain size conditions (e.g., Gibbins and others, 2007a; b). However, the applicability of drift studies on small streams to larger systems such as the Colorado River (>10,000ft^3/s) is tenuous, and few large river drift data are available (Kennedy and others, 2014b). Bed sediment conditions also vary substantially throughout the Colorado River (gravels in Glen Canyon, sand deposits in Marble Canyon, etc.). Thus, the frequency with which one or more of these three catastrophic drift conditions occurs likely varies widely throughout Glen, Marble, and Grand Canyons. In order to quantify and predict the response of invertebrate drift to flow conditions within specific habitats throughout the Colorado River, studies that couple high resolution measurements of shear stress, sediment grain size, and invertebrate drift are needed.

These results will provide important information for characterizing the spatial and temporal dynamics of the aquatic invertebrate community in the Colorado River and, by extension, the food base available to drift-feeding rainbow trout and humpback chub populations. For example, research conducted in Glen Canyon demonstrates that Glen Canyon Dam acts as a "discontinuity" (Ward and Stanford, 1983; Stanford and Ward, 2001). Essentially, the dam creates conditions akin to a headwater stream, in that there is no upstream source of macroinvertebrate colonists. This is in contrast to most large river reaches, including the Colorado River in Marble and Grand Canyons, where invertebrate drift from upstream provides a principal source of colonists. Populations in the Glen Canyon tailwater are therefore maintained entirely by individuals flying, crawling, or swimming against the current from downstream (Müller, 1982). As a result, species accumulation in Glen Canyon increases with distance downstream of the dam, as more invertebrates are able to colonize and maintain persistent populations. This affects invertebrate drift concentrations, benthic populations, and the food base available to fish, such that the number of invertebrates entering the drift varies as a function of distance from the dam, and very low drift concentrations are found in the first ~ 4 miles of the tailwater (Muehlbauer and others, 2013; Fig. 3).

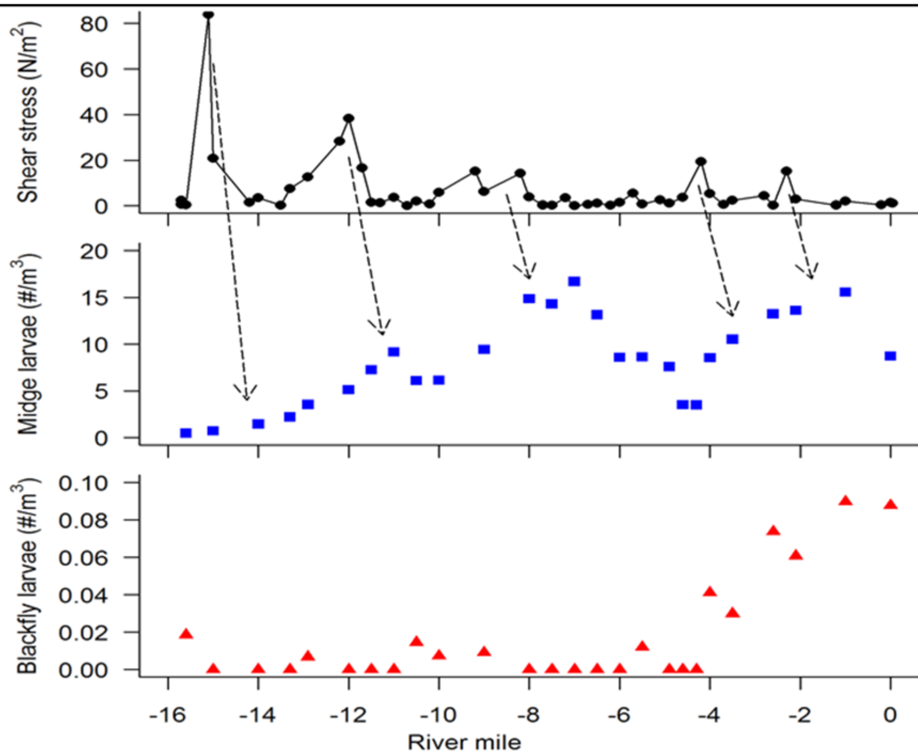

Figure 3. Colorado River bed shear stress at 8000 ft^3/s discharge in May 2013, relative to midge and blackfly drift concentrations at 26 drift sampling sites between Glen Canyon Dam and Lees Ferry. Invertebrate drift is highly variable in space and is directly related to shear stress conditions. Drift also increases exponentially with increased distance downstream of Glen Canyon Dam.

The low diversity of the invertebrate foodbase in Glen Canyon may also have tangible effects on drift characteristics in this tailwater. For instance, tailwaters with high diversity may experience less pronounced seasonal and spatial variation in drift availability, as a more diverse invertebrate assemblage will contain species that drift and emerge at different times of year, and from a greater diversity of habitats. This may benefit fish populations by providing a more consistently-available food base (McKinney and Speas, 2001). Thus, better characterizing invertebrate drift not only in Glen Canyon, but also in tailwaters throughout the Intermountain

West, will better inform how fish in Glen, Marble, and Grand Canyons may be affected by the low diversity and productivity of the aquatic foodbase present in the Colorado River.

Monitoring algae production in Glen, Marble, and Grand Canyon

Algae represent the base of the food web in Glen, Marble, and Grand Canyons, feeding the invertebrates that, in turn, become food for fish (Cross and others, 2011; Donner, 2011; Cross and others, 2013; Wellard Kelly and others, 2013; Seegert and others, *in press*). In cooperation with University of Wyoming and Montana State University, GCMRC has developed an approach for continuously measuring rates of algal production in the River at reach-scales using detailed dissolved oxygen budgeting (Hall and others, 2010; Hall and others, 2012; Hall and others, In review). In collaboration with GCMRC's water quality monitoring program (Project 2), we have been continuously measuring dissolved oxygen concentrations at six sites (RM 0, 30, 61, 87, 166, and 225) since 2008–2010 (Fig. 4). Continued monitoring of algae production at these sites in FY15–17 will identify the effects that ongoing adaptive experimentation have on a key resource that is at the base of Colorado River food webs. Further, continuous estimates of algae production from Glen, Marble, and Grand Canyons will help inform insect emergence and invertebrate drift data that is also described in this Project.

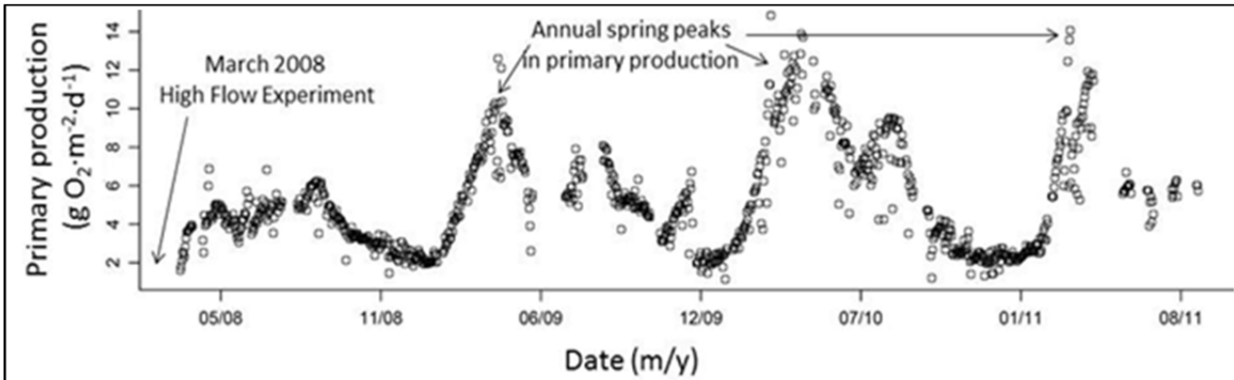

Figure 4. A nearly continuous record of algae production for the Glen Canyon tailwater, from 15 March 2008 to 10 August 2011. Although dissolved oxygen monitoring commenced after the March 2008 HFE, these data still provide insight into the effect of that HFE on algae production in the reach. For example, 2008 is the only year in the record that lacks a strong spring peak in algae production, likely because the HFE scoured benthic substrates and reduced the biomass of algal primary producers. Breaks in the record are due to equipment failure. Rob Payn, Montana State University, unpublished data.

C.2. Management Background

An important part of maintaining native and desired non-native fish populations is ensuring there is an adequate food supply to support them. This need has been translated into policy as part of the strategic plan of the Glen Canyon Dam Adaptive Management Program:

> *Goal 1: Protect or improve the aquatic foodbase so that it will support viable populations of desired species at high trophic levels.*

The research and monitoring described in this Project is motivated by Goal 1, and informed by Protocol Evaluation Panels (PEP) conducted in 2001 and 2012. The PEP conducted in 2001 recommended that:

"The food base program needs to be critically reviewed because the current level of understanding about the linkages between lower trophic levels and food availability of native fishes is not adequate to interpret food base data in relation to [Goal 1]." (Anders and others, 2001).

In other words, the 2001 PEP recommended that GCMRC 'unpack' the GCDAMP's Goal 1 for foodbase by first demonstrating whether populations of desired species at higher trophic levels would even benefit from protection or improvement of the aquatic foodbase. Although it might seem like a purely academic exercise to demonstrate that animals populations are limited by their food, in fact, factors other than food can often limit animal populations. For example, because cold water temperatures during spring and summer prevent native fishes from spawning in the River, the supply of recruits to adult mainstem populations is limited by the capacity of tributaries to produce young fish. Thus, one might expect the food requirements of native fish populations in Grand Canyon to be far lower than the foodbase is capable of supporting, because native fish populations might be limited by the availability of suitable spawning and rearing habitat. In fact, the food web studies that were motivated by the recommendations of the 2001 PEP demonstrated that fish populations throughout Glen, Marble, and Grand Canyons were consuming virtually all of the available midge and blackfly biomass produced annually (Cross and others, 2013; Kennedy and others, 2013b). Simply put, these recent food web studies demonstrated that fish populations in the River were limited by the foodbase. Further, the simple architecture of the Glen Canyon tailwater food web makes it inherently unstable and susceptible to large changes following disturbances, including High Flow Experiments (HFE) (Cross and others, 2013). Thus, food web studies described in Cross and others (2013) demonstrated that fish populations will likely benefit from *improvement* of the aquatic food base.

Project 5.1 seeks to identify the specific stressors that are limiting the diversity and productivity of the foodbase so that managers will have a scientific basis for considering how they might go about *improving* the foodbase. Additionally, Project 5.1 describes a flow experiment that might actually improve the foodbase, and could be considered for implementation in FY15–17.

The scope of the research described in Project 5 is also informed by the recommendations of the 2012 PEP. Specifically, that panel recommended that GCMRC:

"Expand monitoring and research beyond the Colorado River mainstem within Glen and Grand Canyons; information from key tributaries and mainstem locations above Lake Powell is critical to understanding the aquatic food webs of the Colorado River and what potential exists for successful alterations to the system."(Carlisle and others, 2012).

Invertebrate drift provides a principal food source for drift-feeding fishes such as humpback chub and rainbow trout, so characterizing this component of the aquatic foodbase is critical to understanding the state of fish populations in the Colorado River in Glen, Marble, and Grand Canyons. The proposed monitoring and research outlined in Project 5.2 is dedicated to understanding the conditions, habitats, and times under which invertebrate drift occurs. As such, it is directly related to Goal 1.

Finally, the data collection and methods employed by the GCMRC Foodbase Group represent the state-of-the-art in terms of aquatic monitoring and research, as described in section E, below. This monitoring and research therefore reflects another of the 12 goals of the Adaptive

Management Program:

Goal 12: Maintain a high quality monitoring, research, and adaptive management program.

C.3. Key Monitoring and Research Questions Addressed

Stated simply, the overarching question we propose to answer through the work described in this project is “why is the diversity and productivity of the aquatic foodbase in Glen, Marble, and Grand Canyons so low?” Each of the questions enumerated below represents a component of this question. The numbers in italics at the end of each question represent the project sub-elements associated with answering each question.

1. Do water level stage changes due to hydropeaking lead to aquatic invertebrate recruitment limitation, preventing recolonization of the Colorado River by EPT? *5.1.1, 5.1.2, 5.1.5*
2. Is recruitment limitation a primary cause of low midge and blackfly production in the Colorado River? *5.1.1, 5.1.2, 5.1.5, 5.1.6*
3. What factors generally control EPT distributions in rivers, and are conditions different in the Colorado River in Glen, Marble, and Grand Canyons compared to other systems in the Upper and Lower Basin? *5.1.3, 5.1.4, 5.1.7, 5.1.8*
4. Does higher invertebrate diversity in a tailwater result in larger trout and higher densities, or less variable trout populations over time? *5.1.4*
5. Do processes and physical characteristics of drift habitat (flow dependent distributions of bed shear stress and distribution of substrate type) vary among reaches, and does this explain differences in observed concentrations of invertebrate drift? *5.2.3, 5.2.4*
6. How does invertebrate drift in Glen, Marble, and Grand Canyons vary spatially and seasonally, and with respect to emergent insect densities, dam management, and fish population dynamics? *5.2.1, 5.2.2, 5.2.3*
7. Is the rate at which species accumulate and drift concentrations increase with distance from the dam consistent across tailwaters, or is this rate unusually low downstream of Glen Canyon Dam? *5.2.1, 5.2.5*
8. Are the spatial patterns and functional relationships between physical controls and invertebrate drift downstream of Glen Canyon Dam unique, or more broadly applicable to other tailwaters in the Colorado River Basin? *5.2.3, 5.2.4, 5.2.5*
9. Does higher invertebrate diversity in a tailwater result in less variable seasonal and spatial patterns of drift? *5.2.1, 5.2.5*
10. How does algae production vary seasonally, with HFEs and other flow changes, and longitudinally throughout Glen, Marble, and Grand Canyons? *5.3.1, 5.3.2, 5.3.3*

C.4. Hypotheses Explaining Aquatic Invertebrate Productivity and Diversity

We present five hypotheses that could explain why aquatic insect diversity is low downstream of Glen Canyon Dam. We also note whether any of these diversity hypotheses can also explain why production of midges and blackflies is low. Numerous other hypotheses can explain just the low production, but not the low diversity, of the Colorado River, such as nutrient dynamics, high turbidity/low algae, or armoring of the bed; however, these types of production-related hypotheses are not included here because they were a major focus of earlier foodbase research (Cross and others, 2013; Kennedy and others, 2013b). After each hypothesis is presented, we outline management implications if the hypothesis is true.

Hypothesis 1 (**H1**). *Cold water temperatures of the Colorado River prevent EPT taxa from completing their lifecycle.*

Rationale: **H1** specifically attributes the absence of EPT taxa to cold water temperatures. Summer water temperatures of the post-dam Colorado River are colder than the tributary streams in Grand Canyon that support populations of EPT taxa (Voichick and Wright, 2007). Larval stages of EPT taxa from tributaries may be able to survive and grow in the mainstem in spite of cold water temperatures, as evidenced by the persistence of EPT in the tributaries even though winter temperatures in these tributaries are similar to the mainstem. However, consistently cold temperatures throughout spring and summer may prevent EPT taxa from completing their life cycle in the mainstem, particularly due to the sensitivity of key life stage transitions, such as the transition from egg to larva, that occur at these times (Elliott, 1978). Although **H1** may explain why EPT taxa are absent, this hypothesis cannot by itself explain why production of midges and blackflies is low, because many cold water streams and rivers have high invertebrate production (Huryn and Wallace, 2000).

Management Implications: Under **H1**, installation of a selective withdrawal structure on Glen Canyon Dam would be required to increase river temperature and allow populations of EPT taxa to complete their life cycle and establish naturally recruiting populations in the Colorado River. Alternatively, EPT taxa may colonize the Colorado River in future years if climate change results in consistently lower elevations in Lake Powell and warmer releases from Glen Canyon Dam. Warmer water temperatures would also be expected to increase the production of midges and blackflies (Huryn and Wallace, 2000).

Hypothesis 2 (**H2**). *Unnatural water temperature regimes are out of phase with the seasonal timing of key EPT life stage changes.*

Rationale: **H2** ascribes the absence of EPT taxa to the unnatural seasonal timing of temperature regimes rather than to cold temperatures *per se* (Olden and Naiman, 2010). For example, in the Glen Canyon tailwater, maximum water temperatures typically occur in October or November (http://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09380000), whereas in tributaries maximum water temperatures occur in June–July when air temperatures are highest (Voichick and Wright, 2007). If annual maximum temperatures or specific temperature thresholds (e.g., day of year when 55 °F is reached) are the primary cues that trigger insect emergence and other key life stage changes, then the unnatural timing of water temperature regimes may be causing critical delays in the life cycle of EPT taxa. For example, unnatural water temperature regimes might be causing EPT taxa to emerge from the Colorado River during winter months when air temperatures are freezing. However, **H2** cannot explain why midge and blackfly production is low, because citizen science emergence monitoring indicates midge and blackfly emergence occurs throughout the spring and summer, and peaks in late June around the summer solstice (Kennedy and others, unpublished data). That is, midge and blackfly emergence appears related to day length, and the unnatural seasonal timing of Colorado River water temperature regimes does not appear to be causing abnormal delays in emergence of these insects.

Management Implications: The management implications of **H2** are similar to **H1**. However, the specifications on a selective withdrawal device, such as the number of units outfitted, may differ if the management objective is re-creating the pre-dam maximum and minimum temperatures (**H1**) vs. more natural seasonal timing of temperature thresholds (**H2**).

Hypothesis 3 (**H3**). *Dispersal limitation prevents EPT taxa native to the Colorado River from colonizing Glen, Marble, and Grand Canyons.*

Rationale: **H3** posits that native EPT taxa are capable of inhabiting the Colorado River in Glen, Marble, and Grand Canyons, but they have not re-colonized because suitable source populations are distant. For example, Cataract Canyon is >100 river miles from Glen Canyon and is separated from it by a large dam and reservoir. However, there are several assumptions implicit in **H3.** First, there is an assumption that load-following flows (i.e., unconstrained hydropeaking) or some other historical bottleneck extirpated EPT taxa from segments downstream of Glen Canyon Dam. Second, there is the assumption that this bottleneck is no longer present, most likely due to flow changes implemented by the 1996 Record of Decision. **H3** also assumes that EPT species currently present in Grand Canyon tributaries differ from species historically present in the Colorado River mainstem. That is, **H3** assumes that EPT taxa in tributaries are incapable of serving as source populations for mainstem re-colonization. **H3** is the first hypothesis presented that attributes the absence of EPT to flow management, specifically to flow management policies that have not been in place for more than two decades. However, **H3** cannot explain why EPT taxa present in tributaries have not colonized the mainstem river, especially at downstream locations where water temperature regimes are somewhat naturalized. Further, **H3** cannot explain why production of midges and blackflies within the mainstem is low.

Management implications: Reintroductions of invertebrates from upper basin segments and tailwaters is a logical next step in the adaptive management process under **H3**. Note that a similar dispersal limitation hypothesis provides the basis for ongoing humpback chub translocations in Grand Canyon tributaries (Holton, 2008; Spurgeon, 2012; Trammel and others, 2012). That is, humpback chub translocations are occurring (Shinumo Creek, Havasu Creek, Upstream of Chute Falls in the Little Colorado River), and are planned (Bright Angel Creek), because it is assumed that dispersal limitation is preventing humpback chub from inhabiting these locations. Likewise, a dispersal limitation hypothesis motivates recent translocations of razorback sucker (*Xyrauchen texanus*) into western Grand Canyon.

Hypothesis 4 (**H4**). *Hydropeaking causes catastrophic drift and high mortality of EPT larvae, thereby preventing populations from becoming established.*

Rationale: Invertebrate drift is a fundamental aspect of the overall life history of aquatic insects because drift allows for rapid re-colonization of benthic substrates by larvae following egg-laying by emergent adults. Invertebrate drift is often triggered by changes in discharge, and the daily changes in discharge associated with hydropeaking may cause exceptionally high rates of drift for EPT taxa that have catastrophic consequences for their populations. **H4** is informed by recent research in Glen Canyon that demonstrated the strong effect that hydropeaking can have on invertebrate drift concentrations (Kennedy and others, 2014b). Specifically, during summer hydropeaking, Kennedy and others (2014b) found that more than 1% of midge and blackfly larvae for the entire 16 mile tailwater were being exported past Lees Ferry each day. **H4** posits that over invertebrate life spans (months to years), catastrophic drift (Anderson and Lehmkuhl, 1968) associated with hydropeaking is a critical source of mortality. Note that **H4** can also reasonably explain why production of midges and blackflies is low, because Kennedy and others (2014) demonstrated high rates of drift for these taxa in Glen Canyon. However, **H4** implicitly assumes that EPT taxa on whole are susceptible to catastrophic drift to a much greater extent than midges and blackflies, such that EPT have become extirpated but midges and blackflies have not. **H4** is the first hypothesis presented that attributes the absence/rarity of EPT to existing flow management policies.

Management Implications: **H4** suggests that a new flow action, constraining the daily range of hydropeaking to reduce catastrophic invertebrate drift, be considered. These constraints would likely need to occur for substantial portions of the year under **H4**, because aquatic insects are susceptible to catastrophic drift throughout their larval lifespan.

Hypothesis 5 (**H5**). *EPT taxa are recruitment limited, because hydropeaking causes high egg mortality.*

Rationale: Hydropeaking from Glen Canyon Dam creates a large varial (intermittently wetted) zone along shorelines. Because the Colorado River in Glen, Marble, and Grand Canyon is canyon bound and the tributaries that join the river all have comparatively low discharge, the size of the varial zone does not appreciably decrease with distance downstream. For example, daily stage change during summer hydropeaking is around 2 feet at both the Lees Ferry gage and the Diamond Creek gage 225 miles downstream. Thus, although water temperature regimes become more naturalized with distance downstream, the effect that hydropeaking has on the stability of shoreline habitat does not attenuate with distance from the dam.

H5 attributes the absence of EPT and the poor health of the invertebrate assemblage to the width of the varial zone, similar to earlier investigations (Blinn and others, 1995), but **H5** goes a step further and focuses on the effect that unstable shorelines have on a specific life stage of aquatic insects—eggs. **H5** implicitly assumes that egg-laying by EPT taxa occurs principally along shorelines, because if egg-laying by EPT taxa was occurring in the main channel then egg survival would be unaffected by daily changes in stage. This assumption of egg-laying along shorelines seems reasonable given the life history of aquatic insects, and EPT taxa in particular. Aquatic insects concentrate along shorelines immediately after emergence, and mating swarms of aquatic insects are associated with vegetation and other physical structures along shorelines (Gratton and Vander Zanden, 2009; Muehlbauer and others, 2014). Females likely choose to oviposit (lay eggs) in the first ideal habitat they encounter as they travel back to the water from land, so it makes intuitive sense that most egg laying would also occur in the varial zone near shorelines. Further, the specialized egg-laying behaviors of some EPT taxa necessitate this critical life history step occur along shorelines. For example, mated females of the ubiquitous mayfly genus *Baetis* land on an emergent rock in fast water, then crawl a couple of inches under the water's surface and affix a cluster of eggs to the rock (Encalada and Peckarsky, 2012). In fact, Encalada and Peckarsky (2012) were able to double the number of *Baetis* larvae present in 50 m stream reaches simply by doubling the number of rocks available for *Baetis* egg-laying, and to reduce by half the number of *Baetis* larvae present in stream reaches by eliminating the emergent rocks that adults require for egg-laying. This example highlights the critical role that recruitment plays in determining aquatic insect population dynamics.

H5 posits that EPT taxa downstream of Glen Canyon Dam are recruitment limited, because hydropeaking negatively affects habitat quality along the shorelines where egg-laying is assumed to occur. Note that **H5** also assumes that the eggs laid by EPT taxa in the varial zone, and which are subjected to daily drying, will experience high mortality prior to larval development. This assumption of high mortality also seems reasonable given typical summertime air temperatures in Grand Canyon that can exceed >110 °F, with ground temperatures >130 °F. **H5** can also explain why midge and blackfly production is low, because these taxa will also be susceptible to high egg mortality and recruitment limitation if egg laying occurs principally along shorelines.

***Management implications*:** Both **H5** and **H4** posit that hydropeaking is responsible for the absence/rarity of EPT taxa and the low production of midges and blackflies. However, mitigating the effects of hydropeaking under **H5** is fundamentally different than mitigating the effects of hydropeaking under **H4**. Specifically, **H5** implies that shorelines only need to be stable for sufficient time to overcome the negative effects that recruitment limitation is having on the diversity and productivity of the aquatic food base.

Support for Hypothesis 5 (**H5**)

As a first step toward framing the problem of low aquatic invertebrate diversity and productivity in the Colorado River, we have focused on the role that individual stressors may be playing in driving observed patterns of insect diversity and productivity. Although there are likely significant interactions among stressors such as temperature and flow (Olden and Naiman, 2010), isolating the predominant, most-impactful stressor will represent a major step towards understanding how to go about improving the aquatic foodbase. Likely each stressor represents an environmental filter that limits invertebrate populations to some extent (Poff, 1997), with the cumulative effect of all these stressors resulting in the low diversity and productivity conditions in the Colorado River. Removing all these stressors is infeasible; however, identifying and ameliorating the stressor that has the greatest filtering effect on invertebrate populations may be sufficient to impart large and beneficial change to the aquatic invertebrate diversity and productivity of the Colorado River ecosystem.

Managers also have limited ability or willingness to actively mitigate some of the stressors we identified. For example, the high-cost (>$150M) and risks (invasion by warm-water nonnatives) associated with installation and use of a selective withdrawal structure on Glen Canyon Dam mean active temperature mitigation is unlikely (**H1** and **H2**). Mitigating and testing the dispersal limitation hypothesis (**H3**) could be accomplished through translocations of insects from other river segments, but, in our opinion, this hypothesis requires too many unreasonable assumptions, none of which are actually testable, to warrant serious consideration. In contrast, mitigating the negative effects of hydropeaking under both **H4** and **H5** is logistically possible. However, the diversity assumption implicit in **H4** is that EPT are much more susceptible to catastrophic drift than midges and blackflies. Project 5.2 describes research and monitoring that will address uncertainties relative to **H4**. However, while it may be a lesser filter affecting species distributions within small scales or certain reaches of the river (Poff, 1997), it seems unreasonable to expect that catastrophic drift is the predominant stressor limiting EPT colonization throughout Glen, Marble, and Grand Canyons.

There are two assumptions that are implicit in **H5**: that substantial egg-laying by adult insects occurs near shorelines, and that mortality of eggs subjected to drying is high. Because aquatic insects have a biological imperative to return to the water as quickly as possible to lay their eggs and are generally not well adapted to life outside of water, both of these assumptions seem reasonable. Further, both assumptions can be tested with field and laboratory studies.

Given management realities as well as the assumptions embedded in many of the five hypotheses, we focus on testing **H5** in Project 5.1 and with the flow experiment we propose, because emergence and egg-laying of aquatic insects are very poorly studied processes, particularly in the context of river regulation and hydropeaking. Most importantly, mitigating potentially negative effects of recruitment limitation, assuming **H5** is true, has the highest probability of leading to a large and positive increase in insect diversity and productivity, even as other stressors persist.

Proposed Flow Experiment

There are numerous flow experiments that could be developed to experimentally test the validity of **H5**. However, a central tenet of adaptive management is to focus on testing alternative policies, as opposed to simply testing hypotheses (Walters, 1986), and many potential flow experiments are impractical from a policy standpoint. For example, year-round stable flows would represent a definitive test of **H5**, but such an experiment would likely lead to a large cohort of juvenile rainbow trout (Korman and others, 2012), with potentially negative consequences for humpback chub populations. Thus, year-round stable flows do not represent a good test of a policy option that might eventually be considered for long-term implementation, because negative or undesirable effects on other resources such as rainbow trout and hydropower production may outweigh the benefits that year-round stable flows might have on insect diversity and productivity. Although stable summer flows have occurred in 2000 and 2011, foodbase monitoring techniques were not well developed in 2000, and only rudimentary monitoring was in place in 2011 due to budget cuts in the foodbase program. Thus, it is not possible to draw inferences about **H5** using invertebrate monitoring data from these years.

Alternatively, the validity of **H5** could be evaluated with a shorter duration block of steady flows. For example, the time of year with the highest rates of emergence and egg-laying could be identified (mid-June–mid-July), and then stable flows that encompass this entire emergence period could be implemented. However, emergence timing varies widely among EPT taxa, and a month-long block of stable flows might positively affect egg survival for some species, but other species that emerge and lay eggs during other times of year would not be affected by this experiment. Additionally, short-lived species such as midges and *Baetis* mayflies have multiple generations per year, so this experimental design might positively affect egg survival for one generation of these short-lived species, but population dynamics would likely be determined by the fate of other generations that are emerging at other times of year. Thus, this type of short-duration experiment does not represent a good test of a policy option that might eventually be considered for implementation, because it is unlikely that a month-long block of steady flows will significantly increase invertebrate diversity or productivity.

We propose a novel experimental design for testing the validity of **H5** that involves stable flows every weekend from May through August (34 days total). The discharge on weekends would be the minimum discharge for that month, which will ensure that the insect eggs laid during weekends will never be subjected to drying due to lower water levels at any point prior to larval development. No change in monthly volumes, ramping rates, or the daily range in discharge during weekdays would be required as part of this experiment. To offset the smaller water releases that would occur during weekends within a given month, larger releases would need to occur during the weekdays within a given month. Ideally, and pending environmental compliance discussions and approval, this flow experiment could be initiated in 2015. Results from 2015 would be available in early 2016 and should be sufficient to provide baseline support or opposition for any continuation of the flow experiment in summer 2016 and future years.

The timing of the proposed experiment is informed by citizen science light trapping results demonstrating that midges, and to a lesser extent blackflies and micro-caddisflies (Order Trichoptera, Family Hydroptilidae), are emerging from the mainstem throughout the summer period from May to August (Kennedy unpublished data). This experiment will provide an ideal egg-laying environment of stable water levels along shorelines, at regularly-timed intervals throughout the emergence and egg-laying season. Thus, if the mechanisms and assumptions underlying **H5** are true, this flow experiment should elicit both short-term (month-to-month) and long-term, (year-to-year) population-level responses from aquatic insects, as more eggs hatch into larvae, leading to more adults, which lay the eggs that set the stage for more successful cohorts of future generations. Importantly, the flow experiment we propose also represents a viable mitigation strategy, because it is likely to benefit the target resource, and impacts to other non-target resources such as hydropower may be minimal/acceptable.

D. Proposed Work

Sixteen proposed project sub-elements are described in this proposal. For ease, these sub-elements are partitioned into three broader project elements: 1) tasks principally related to studying the factors limiting diversity and production of the invertebrate foodbase, 2) tasks principally related to characterizing the factors controlling invertebrate drift, and 3) tasks related to monitoring algae production in the Colorado River.

Some of the project sub-elements described here involve fieldwork in the Upper and Lower Colorado River Basin, outside of Glen, Marble, and Grand Canyons (Project Elements 5.1.7, 5.1.8, and 5.2.5). We recognize that these sub-elements therefore may not be eligible for funding by GCDAMP. Consequently, supplemental funding for these projects has been requested from sources external to the GCDAMP. These project sub-elements are noted by the text "**Submitted for non-GCDAMP funding.*" We have chosen to incorporate these project sub-elements into this GCDAMP proposal because, regardless of their ultimate source of funding, they represent a critical component of the overall body of work we propose to carry out in FY15–17, and will be crucial in providing insight into the remaining project elements we propose for GCDAMP funding.

D.1. Project Elements

Project Element 5.1. Is aquatic insect diversity and production recruitment limited?

Here, we present research and monitoring focused on evaluating the validity of **H5**, described in section C.4 above. This work includes field experiments and modeling that will directly address the assumptions that are implicit in this hypothesis. The strength of our inferences will be significantly increased if these studies are accompanied by the proposed flow experiment; however, these studies will provide insights into the validity of **H5**, regardless of whether the flow experiment is also implemented. Because EPT taxa are virtually absent from the Colorado River in Glen, Marble, and Grand Canyons, we also propose field studies of insect emergence and egg-laying in other segments of the Colorado River that support these taxa.

Project Element 5.1.1. Insect emergence in Grand Canyon via citizen science

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
David Lytle, Associate Professor, Oregon State University

The citizen science sampling of insect emergence initiated by Kennedy in 2012 has yielded an unprecedented dataset of spatial and temporal patterns in aquatic insect emergence throughout 225 miles of Grand Canyon. These data are also beginning to shed light on how flow management affects the critical adult life stage of aquatic insects. This project has also become a powerful outreach tool for communicating Grand Canyon science, and the important role that adaptive management plays, to dozens of river guides and thousands of passengers annually. In many ways, this dataset has been the basis for the research and questions described in this proposal, and we propose to continue this citizen science monitoring in FY15–17. In addition, if flow management changes aimed at increasing insect productivity and diversity in the Colorado River are initiated, data from this monitoring program will be essential in tracking any changes to aquatic insect populations.

Project Element 5.1.2. Quantifying the effects of hydropeaking on oviposition and egg mortality

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC

The main focus of this project element is addressing the two assumptions that are implicit in **H5**. Specifically, this project will quantify 1) the proportion of egg-laying by aquatic insects that occurs in the varial zone relative to permanently inundated habitats, and 2) rates of mortality for eggs that are subjected to daily drying. Observational and field studies of egg-laying will be conducted at sites where the varial zone is wide vs. narrow, and sites where daily flow minima occur during daytime hours vs. nighttime hours. Field studies on egg mortality will be complemented by more controlled laboratory studies on egg mortality (see Project Element 5.1. 6). Studies by Encalada and Peckarsky (2012) and Deutsch (1984) provide examples of methods and approaches that can be used to study egg-laying and egg-mortality, although some innovation and new methods will likely be required for the unique conditions present in the Colorado River. Specifically, we anticipate field studies that will make use of colonization substrate trays for quantifying egg laying at certain locations within the varial zone, and possibly enclosures that allow in situ egg laying to be differentiated from egg deposition via drift from upstream.

Project Element 5.1.3. Synthesis of stressors and controls on EPT distributions

Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Scott Miller, Director, National Aquatic Monitoring Center, Bureau of Land Management

All the hypotheses described above are predicated on an understanding of the stressors and controls that affect the ability of insects to colonize, reproduce, and persist in aquatic ecosystems. The hypotheses we presented are based on sound science for aquatic insects in general; however, in moving toward potential mitigation strategies that will promote colonization or increased production of target species, a better understanding of species-specific traits and stressors will be required (Table 1). We anticipate this synthesis providing general information that is applicable across a suite of EPT taxa; however, we will also use this effort to identify and characterize taxa that could be candidates for colonization of the Colorado River downstream of Glen Canyon Dam, based on their predicted response to the conditions present in this ecosystem.

Table 1. Life History Information for Select Aquatic Insect Taxa. Information on midges and blackflies is specific to the sub-families (midges) or species (blackflies) that are present and widely distributed in the Colorado River. Life history information for representative genera from Ephemeroptera, Plecoptera, and Trichoptera are also presented, even though these taxa are not present in the Colorado River in Grand Canyon. This type of species-specific information will inform the development of field studies and provide insights into invertebrate population

responses to the flow experiment we have proposed. Data from Merritt and others (2008).

Life Trait	Midges (Chironominae, Orthocladiinae)	Blackflies (Simulium vittatum complex)	Ephemeroptera (mayflies) Baetis	Plecoptera (stoneflies) Hydroperla	Trichoptera (caddisflies) Hydropsyche
Feeding mode	Collector-Gatherer	Filter feeder	Collector-gatherer	Leaf shredder, then predator	Filter feeder
Generations per year	Multiple	One or multiple	Multiple	One	One
Egg-laying location	Water surface	Below water line on vegetation	Shallow riffles, under stones	Head of riffles	Submerged object
Pre-egg laying	1-2 days	Variable, requires blood meal	1 day	2-5 days	A few days
Fecundity (eggs per female)	1000-2000	300-600, clumps from many females	~1000	150-300 per egg mass	300-500
Egg incubation	Days to weeks	Days to weeks	Weeks	Weeks-months	Days-weeks
Notes	Eggs masses often float	Overwinters as diapausing egg	Hatching period highly variable	Synchronous hatching	

Project Element 5.1.4. Synthesis of the aquatic foodbase, and its effects on trout populations, in western US tailwaters

Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Scott Miller, Director, National Aquatic Monitoring Center, Bureau of Land Management

This project element will follow an approach similar to the tailwater synthesis project being led by Kim Dibble (see Project 9). That synthesis of trout population dynamics has yielded important insight into how dam management affects trout populations, and has been useful in putting the rainbow trout fishery in Glen Canyon and the operations of the Glen Canyon Dam in context. We will conduct a similar synthesis of aquatic food base conditions in western tailwaters. Some data are already available as a result of Dibble's work, and much of these data were provided by Scott Miller; however, the food base synthesis will naturally have a somewhat different focus from that project. Specifically, in our synthesis we will accomplish the following objectives: 1) describe variation in invertebrate assemblages among tailwaters, 2) use a variety of modeling approaches to identify the role that physical factors (i.e., temperature, flow regime) vs. regional species pools (i.e., **H3**) play in structuring invertebrate assemblages in tailwaters, and 3) describe the relationship between invertebrate diversity and overall productivity of invertebrate assemblages to determine whether a more diverse assemblage downstream of Glen Canyon Dam will likely lead to greater prey resource availability for fishes. Additionally, we will collaborate with Dibble, and directly link information on invertebrate assemblages among tailwaters to the trout population dynamics information she is synthesizing, to evaluate whether tailwaters that support healthy invertebrate assemblages also have more or larger trout, or more stable trout populations. Successful completion of this project will require additional data collection from published journal articles, government reports, and databases, as well as further interaction and data gathering from state, federal, and academic researchers across these western tailwaters.

Project Element 5.1.5. Natural history of oviposition for species present in Grand Canyon

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Eric Kortenhoeven, Ecologist, USGS, GCMRC
Anya Metcalfe, Ecologist, USGS, GCMRC

To understand how environmental stressors affect the populations of aquatic insects present in Grand Canyon, a better understanding of their life history is required. For instance, additional, observational information on the oviposition (egg-laying) behavior of black flies and midges in the Colorado River in Grand Canyon will help support or discredit the hypotheses listed above, and will inform the extent to which alterations to flow management may increase production of the aquatic food base.

Project Element 5.1.6. Laboratory studies on insect oviposition and egg mortality associated with changing water levels

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Adam Copp, Ecologist, USGS, GCMRC

Many of the hypotheses listed above are based on mortality at key insect life stages, particularly the effect of desiccation on egg-mortality (**H5**). Lab or experimental mesocosm studies are highly amenable to isolating such effects and providing conclusive data on the impact of individual stressors, such as the desiccation time and temperature at which 50% (a clinical threshold for mortality) of midge or blackfly eggs become non-viable.

Project Element 5.1.7. Comparative emergence studies in Upper Basin using citizen science light trapping

***Submitted for non-GCDAMP funding**

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC

Citizen science emergence monitoring in Grand Canyon (Project Element 5.1.1) will provide information on insect population response to Glen Canyon Dam operations; however, it is difficult to put the temporal and spatial patterns present in these data into context without comparable data from other regulated and unregulated rivers that have different characteristic flow regimes. Thus, we propose to carry out similar studies in Upper Basin tailwaters including Flaming Gorge Dam, Fontenelle Dam, and Navajo Dam. We will also collaborate with citizen scientists to quantify insect emergence in segments that are unregulated, such as the Green River in Desolation-Gray Canyon, the Colorado River in Westwater and Black Rocks, and Cataract Canyon. These data will elucidate the degree to which unique operations of Glen Canyon Dam affect insect behaviors and life stages, and the degree to which certain behaviors and population dynamics are consistent across segments of the Colorado River Basin. Note that the three years of citizen science emergence monitoring that we have acquired from Grand Canyon (2012–2014) will provide an experimental ‘control’ in the event the flow experiment we propose is implemented. Citizen science monitoring in the San Juan River was already initiated in April 2014 in collaboration with Grand Canyon Youth, and will occur through FY14 and, ideally, into future years as well. As with the Grand Canyon citizen science monitoring, we expect this collaboration to also provide a large outreach benefit to the GCDAMP.

Project Element 5.1.8. Natural history of oviposition for EPT via studies in the Upper Basin

***Submitted for non-GCDAMP funding**

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC

As described in Project Element 5.1.5, understanding the life history behaviors of aquatic insects will provide useful information for predicting insect population responses to flow management. For midge and blackfly species, these studies can be done in Grand Canyon. However, for target EPT taxa that are not currently present in Grand Canyon, their life histories must be studied in river systems where they are extant. The closest segments where these species are present is the Upper Colorado River Basin, specifically tailwaters such as those downstream of Flaming Gorge, Fontenelle, and Navajo Dams, and the unregulated Cataract Canyon reach that serves as a proxy for conditions in the pre-dam river. Thus, we propose natural history studies similar to those in Project Element 5.1.5., to be carried out in these Upper Basin segments with a focus on EPT taxa.

Project Element 5.2. Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters

The work described here focuses on studies that predominantly use drift as a method for assessing the condition of the aquatic foodbase. Such measurements represent a more direct metric for quantifying food availability for humpback chub and rainbow trout, both of which are "drift-feeding fish." The purpose of many of the tasks proposed in these sub-elements is to mechanistically describe the factors influencing drift, particularly on small scales that are known hotspots of fisheries interest such as Glen Canyon and at the confluence of the Little Colorado River. Measuring drift is also a well-established method in stream and river ecology, which allows results of these studies to be more easily compared to other river ecosystems. As with the studies proposed in Project Element 5.1, some of the project sub-elements proposed here will also take place in other tailwaters in the Upper and Lower Colorado River Basin, for the sake of comparing conditions in Glen Canyon to representatively similar sites in the region.

Project Element 5.2.1. Continue characterizing and monitoring drift and insect emergence in Glen Canyon

Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC

Monthly invertebrate drift measurements have been taken longitudinally at six stations throughout Glen Canyon (RM -11, -8, -4.9, -3.5, -2.1, 0.2) and laterally at a cross section at Lees Ferry (RM 0) since January 2013. Monthly monitoring of emergent insects using sticky and light trap sampling was also initiated throughout Glen Canyon in January 2014. This monitoring is carried out using published methods developed by our lab group (Kennedy and others, 2013a; Kennedy and others, 2014b; Smith and others, 2014). These monitoring efforts will be used to describe spatial and temporal patterns of drift throughout Glen Canyon and will be compared to similar data we will collect from other tailwaters as outlined in Project Elements 5.2.2 and 5.2.5, below. In addition, the emergent insect monitoring in Glen Canyon will be linked to the citizen science emergent insect study initiated in 2012 (Kennedy and others, 2013a) to provide an unprecedented longitudinal dataset of emergence, from Glen Canyon Dam at RM -16, to Diamond Creek 225 miles downstream. Extending insect emergence monitoring into Glen Canyon will allow us to better identify the role that flow management plays in driving insect population dynamics, because Glen Canyon is unaffected by sediment turbidity. Emergent insect monitoring will also be coupled with the drift data to describe the proportional relationship between concentrations of drifting invertebrates (i.e., food for fishes) and emergent insects (Statzner and others, 1986; Statzner and Resh, 1993) in the Colorado River. Emergent insects are more easily sampled than drift, and better quantifying the nature of this relationship in Glen Canyon and at the Natal Origins sites in Marble and Grand Canyons (as outlined in Project Element 5.2.2, below) will allow the citizen science emergent insect database to be used as a proxy for drift concentrations throughout the Colorado River.

Project Element 5.2.2. Continue Natal Origins drift monitoring in Glen, Marble, and Grand Canyons

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC

Invertebrate drift has been monitored as part of the ongoing fish Natal Origins (NO) project since 2012. Drift samples are taken at all NO sites (RM -3.5, 18.9, 39.5, 60.15, 63.7) and during the run-out of NO trips at RM 63.7, 71.2, 88, 138.6, 166, and 225. Drift data from NO sites will eventually be linked to fish diet, abundance and distribution data collected concurrently with NO quarterly sampling (see Project 9 in work plan). NO drift data will also be used to parameterize rainbow trout bioenergetics models for Glen, Marble, and Grand Canyons (Project 9). High resolution drift monitoring will also be used to build a coarse-scale map of drift patterns throughout the Colorado River, as outlined in Project Elements 5.2.3 and 5.2.4, below.

In FY13–14, 20 drift samples were taken quarterly at each NO site (100 total samples per trip, or 500 per year). In this work plan, sampling effort per site visit will be reduced by ~50% (10 samples per site) to reduce laboratory sample processing burdens. Power analysis indicates this reduction will only marginally affect our ability to draw inferences from the data. Intensive diet sampling was also conducted at each NO site during FY12–14, resulting in 100 samples for rainbow trout gut content analysis per trip, or 400 per year. This diet analysis sampling will be discontinued in this work plan, because the three years of intensive diet sampling are sufficient to describe the relationship between drift concentrations, water clarity, and rainbow trout feeding habits. During the last two years of the NO project (FY15–16), we will predict rainbow trout feeding habits based on drift concentrations and water clarity, rather than continuing with time-intensive fish gut content analysis.

Project Element 5.2.3. Link drift at Natal Origins project transects to channel bed shear stress

Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
Scott Wright, Research Hydrologist, USGS, California Water Science Center

Bed shear stress conditions will be quantified at all drift sites sampled during NO trips (11 total sites). This work can be done over the course of one NO trip using an acoustic Doppler current profiler (ADCP) with standardized methods developed previously in Glen Canyon (Muehlbauer and others, 2013). These hydrodynamic data will also be useful in fish bioenergetics modeling at the NO sites, and in understanding spatial variability in habitat conditions affecting both invertebrate and fish distributions. Further, these data will be used to characterize the functional relationship between physical environmental controls and invertebrate drift at a coarse scale throughout Glen, Marble, and Grand Canyons, as outlined in Project Element 5.2.5, below.

Project Element 5.2.4. Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons

Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
Scott Wright, Research Hydrologist, USGS, California Water Science Center

This task will integrate spatially and temporally-extensive data on aquatic macroinvertebrate drift, bed shear stress, and sediment grain size distributions. Much of the data collection required has already been completed or is ongoing. The critical work remaining for this task is to systematically link available point data on drift and bed shear stress to channel bed grain size estimates at these same locations. Such data can be used to predict the shear stress conditions under which incipient motion of bed sediment will occur for a given substrate habitat patch (Shields, 1936; Parker and Klingeman, 1982; Wilcock, 1996). By comparing variation in macroinvertebrate drift concentrations across habitat patches where sands and gravels are alternately stable or mobilized for given flow conditions, it is possible to determine the effects on drift of "sand blasting," vs. shear stress alone, vs. habitat loss via rock rolling.

We will carry out high resolution, habitat-specific, linked drift-shear stress-grain size data collection at five fishing 'hot-spots' in Glen Canyon (e.g., "4-mile bar" at RM -4.1). These study locations were originally suggested by fishers (Gerald Meyers, personal communication) and were corroborated as drift 'hot-spots' using drift monitoring data (see figure, above). On multiple dates and flow conditions over two years, we will collect data using standardized drift methods (Kennedy and others, 2014b), ADCP velocimetry for shear stress, and photographic methods for bed surface sediment. Using existing Glen Canyon-wide drift and bed shear stress data, along with bed sediment data that will be collected as part of Project 3, these resulting habitat-specific relationships between invertebrate drift concentrations, shear stress, and sediment entrainment can then be scaled up to predict invertebrate drift responses at habitat patches throughout Glen Canyon. To extend these predictions down river, especially into habitat near the LCR of interest for humpback chub management, we will use data from ADCP measurements for shear stress at the NO drift sites, as outlined above in Project Element 5.2.2. Combined with drift and with existing channel mapping data for the LCR inflow reach from Project 3, these data will allow drift predictions to be scaled up at a coarse scale throughout Grand Canyon, especially in reaches of particular interest for fisheries management.

For the study reach in Lower Marble Canyon—and possibly the reaches outlined above for Glen Canyon—invertebrate drift and bed condition will be investigated at a process level. In this reach, drift sampling in short downstream intervals will be conducted concurrently with repeat bed surveys and full water column multibeam echosounder data collection (described in Project 3). These repeat bed surveys will enable identification of areas of the bed where active sand transport may limit benthic invertebrate colonization and areas where colonization may occur but is subject to disturbance. The full water column data may be used to detect invertebrate drift in the water column directly.

Project Element 5.2.5. Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters

***Submitted for non-GCDAMP funding**

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Jeffrey Muehlbauer, Research Ecologist, USGS, GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center

Here, we propose research on invertebrate drift in Glen, Marble, and Grand Canyons, and in other tailwaters of the Colorado River Basin: downstream of Fontenelle, Flaming Gorge, Navajo, Hoover, Davis, and Parker Dams. We will quantify the extent to which the low invertebrate diversity/productivity condition in Glen Canyon is unusual and how invertebrate diversity affects drift dynamics, especially in terms of temporal and spatial variation. We will also quantify how drift concentrations vary among tailwaters that are situated in canyons with different geomorphology than Glen Canyon, and have different flow management policies, such as hydropeaking in Flaming Gorge and Hoover, but not in Fontenelle and Navajo. Finally, we will characterize longitudinal drift and shear stress dynamics downstream of these Upper and Lower Basin dams and conduct seasonal at-a-station drift measurements to characterize the diversity and density of invertebrates entering the drift through time.

Sampling will occur over the course of one or two trips (single sampling), including sites extending approximately every mile from the dam to ~15 miles downstream. In addition, seasonal changes in the drift will be monitored at select stations within these tailwaters, likely proximate to discharge gages. Such seasonal monitoring in the Fontenelle and Flaming Gorge tailwaters would ideally be carried out through a collaborative agreement with other agencies, or by personnel led by Scott Miller and the BLM Bug Lab at Utah State University.

Our group has developed optimized methods for monitoring drift in Glen Canyon (as outlined in the Background and in Project Element 5.1). However, we expect these methods to require some adjustment in the Upper Basin tailwaters, particularly in river reaches that are narrower and shallower than those present in Glen Canyon. Ideally, appropriate drift sampling methodologies would be modified for these sites in consultation and collaboration with Scott Miller, who has experience sampling drift in some of these tailwaters (Miller and Judson, 2014).

One outcome of characterizing drift in other tailwaters will be to better understand the response of the food base that is available to endangered fish species, as relevant to proposed peak flow studies for endangered fish habitat in the Upper Basin (LaGory and others, 2014). Longitudinal and seasonal drift data in these tailwaters will also be useful in comparison to emergent insect data to better link emergent insect dynamics to invertebrate drift concentrations, as discussed in Project Element 1, above. Emergent insect citizen science monitoring in these tailwaters is currently proposed by Kennedy and others, and was initiated on the San Juan River downstream of Navajo Dam in April 2014 in collaboration with Grand Canyon Youth.

Finally, these drift data will be useful in putting observed drift, habitat, and invertebrate diversity patterns in the Glen Canyon Dam tailwater in context. For example, increased understanding of drift in other tailwaters should elucidate the degree to which observed patterns and biological processes downstream of Glen Canyon Dam, such as food limitation of fish populations, zero/low EPT diversity, and rates of downstream colonization are potentially atypical. These studies may also help identify approaches for increasing invertebrate drift availability, which would benefit native and desired non-native fish populations in the Glen-Marble-Grand Canyon reach of the Colorado River.

Project Element 5.3. Monitoring algae production in Glen, Marble, and Grand Canyons

The monitoring described in this project element will synthesize algae production data for

Glen Canyon, maintain dissolved oxygen monitoring at select locations in Glen, Marble, and Grand Canyon, and develop simpler, automated approaches for estimating algae production.

Project Element 5.3.1. Controls of algal production in Glen, Marble, and Grand Canyon

Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Michael Yard, Fisheries Biologist, USGS, GCMRC
Robert Payn, Assistant Professor, Montana State University
Robert Hall Jr., Professor, University of Wyoming

Daily estimates of algal production in Glen Canyon have been computed from 2008–present (Fig. 4). In FY15, we will synthesize these data and develop a manuscript describing the controls of algal production in Glen Canyon. In FY16 and FY17 we will estimate algae production in Marble and Grand Canyon using data from 2011–2015. A manuscript describing controls of algae production in these locations is currently in review (Hall and others, In review), but the period of record for that manuscript only spans 2008–2011 for one location (Diamond Creek) and quarterly estimates for other locations. Notably, the period of record does not include any HFEs.

Project Element 5.3.2. Continuous monitoring of dissolved oxygen concentrations in Glen, Marble, and Grand Canyons

Adam Copp, Ecologist, USGS, GCMRC
Nicholas Voichick, Hydrologist, USGS, GCMRC

In FY15–17 we will maintain our network of continuous dissolved oxygen monitoring stations at six locations in Glen, Marble, and Grand Canyons (RM 0, 30, 61, 87, 166, and 225).

Project Element 5.3.3. Develop automated tools for converting dissolved oxygen data to algal production

Charles Yackulic, Research Statistician, USGS, GCMRC
Edward Stets, Ecologist, USGS, National Research Program
Robert Hall Jr., Professor, University of Wyoming

Stets is the lead, and Hall and Yackulic are collaborators, on a recently submitted USGS Powell Center for Analysis and Synthesis proposal, the purpose of which is to develop automated tools for converting dissolved oxygen data into algal production estimates. If the proposal is successful, one outcome of the synthesis will be automated tools developed specifically for sites in Glen, Marble, and Grand Canyons where we have been continuously monitoring dissolved oxygen since 2008–2010.

D.2. Personnel and Collaborations

Aquatic invertebrate monitoring and research efforts at GCMRC provide important insight into the condition of the Colorado River ecosystem, particularly with respect the foodbase available to fish. However, these studies require the collection of a large number of samples that can demand substantial time to process, necessitating a large staff. Within the GCMRC Aquatic Ecology group, research projects are conceived, designed, and analyzed by principal investigator

Theodore Kennedy. Postdoctoral fellow Jeffrey Muehlbauer also acts as a principal investigator in conceiving and carrying out research projects and analysis, and brings integrated invertebrate ecology, geomorphology, and hydrology expertise to the group. Adam Copp manages sample inventories and databases, maintains the invertebrate drift and water quality monitoring projects, and oversees the day-to-day operations of the lab. Joshua Smith serves as field crew leader, particularly for ongoing research and monitoring projects in Glen Canyon and the Little Colorado River. Eric Kortenhoeven and Anya Metcalfe are responsible for processing light trap samples; they also provide outreach and interface with the citizen scientist river guides who collect these samples. Moriah Evans, Thomas Quigley, and ~3 additional full time, part time, or student technicians are primarily responsible for the lab processing of drift samples. All personnel also take part in field work in support of these projects.

Our group is also taking innovative steps to optimize workflow and minimize processing times. For instance, we have developed a barcoding system to track the status of >6000 samples that are in various stages, from sample collection, to storage, to active processing, to analyzed sample archiving (Copp and others, In review). Since barcoding was initiated in 2012, we have collected an average of 900 drift samples per year, which will be reduced to ~650 samples annually in FY 15–17 with reduced sampling effort for the Natal Origins project. Earlier inefficiencies created a large backlog of samples that we are still processing, but at current rates of 4 hours of processing time per sample we expect our FY15–17 drift processing capacity to be approximately equal to sample collection efforts.

We have also processed ~2000 light trap samples since 2012, at a rate of roughly one sample every 45 minutes. Finally, we have deployed ~2000 sticky traps since 2013 (Smith and others, 2014). Most of the sticky trap samples have not yet been processed because the automated image processing protocol for their analysis is still in active development; however, early tests indicate that processing time should ultimately be only 2 minutes per sample.

This project will utilize and integrate data from, provide data for, and require collaborations with other projects described in this work plan. Specifically, data collection in Projects 2 and 3 related to discharge, temperature, suspended sediment concentrations, channel width, and shoreline inundation will be requisite for successful completion of most of the sub-tasks in Project Elements 5.1, 5.2, and 5.3 outlined in this project. Completion of these tasks will take place with input from geomorphologists Paul Grams and Daniel Buscombe and hydrologist Nicholas Voichick associated with those projects, in addition to Scott Wright from the USGS California Water Science Center. Algae production modeling described in Project Element 5.3 will also occur in collaboration with faculty at Montana State University and the University of Wyoming, as well as USGS scientists affiliated with the National Research Program.

Many sub-tasks within this project will specifically address fisheries questions outlined throughout this work plan. For instance, Project Elements 5.2.2 and 5.2.3 build upon rainbow trout and humpback chub foodbase data needs described by Michael Yard, Josh Korman, and others as part of the Natal Origins project described in Project 9. These data will be used to quantify the availability of invertebrate prey resources at key fish monitoring locations in Glen and Marble Canyons, including at the confluence of the Little Colorado River. Citizen science emergence monitoring data will also inform new proposed studies on terrestrial-aquatic linkages (see Project Element 11.4).

Several of the sub-tasks in Project Elements 5.1 and 5.2 describe a nascent collaboration between GCMRC scientists and the BLM/Utah State University National Aquatic Monitoring Center. The results and output from this collaboration will be invaluable toward the goal of putting the state of the aquatic foodbase in Glen, Marble, and Grand Canyons in the larger context of the Colorado River Basin throughout the Intermountain West.

Finally, David Lytle/Oregon State University is the author of seminal publications on aquatic insect dispersal, aquatic insect response and adaptations to disturbances including floods, and population genetics of insects in arid landscapes (Lytle, 1999, 2001, 2002; McMullen and Lytle, 2012). Collaboration with Lytle on Project Element 5.1 will allow us to put proposed data collections into the broader context of disturbance regimes and aquatic insect life-history evolution.

D.3. Deliverables

This project will yield new scientific insights that are directly relevant to management of invertebrate assemblages and food webs in the River. Our investigations will largely focus on evaluating the validity of one hypothesis (**H5**) that explains the low diversity and productivity of the aquatic foodbase. The flow experiment we propose represents a test of policy option that might ultimately ameliorate the effects that hydropeaking may be having on invertebrate diversity and productivity. Implementation of the proposed flow experiment will also greatly increase the power of the inferences we can draw relative to the validity of **H5**. If the studies proposed for FY2015-2017 yield data that does not ultimately support this hypothesis (i.e., hydropeaking does NOT appear to be the principal stressor limiting the diversity and productivity of invertebrate assemblages), then investigations in 2018 and beyond could focus on evaluating alternative hypotheses, including the dispersal limitation hypothesis (**H3**) through direct translocations of native Colorado River invertebrates. Additionally, the syntheses and field studies we propose in other regulated and unregulated segments of the Basin will yield a list of "candidate" aquatic insect species that are native to the Colorado River that Grand Canyon National Park could consider for translocation.

In general, most of the 16 project elements should result in one or more peer-reviewed journal articles and presentations at scientific meetings; the remaining smaller project elements will provide critical supporting information to larger project elements. These larger project elements describe cutting-edge work in the fields of limnology as well as ecology in general, and the outcome of several of these project elements should be the publication of papers in some of the highest-tier scientific journals.

The studies described in Project Elements 5.1 and 5.2 on emergent and drifting insect dynamics are representative examples of the current trend in ecology toward "big data," or the analysis of very large datasets, as well as the syntheses of data on a large scale from multiple, disparate sources. This work will enable us to characterize aquatic insect and invertebrate dynamics in the Colorado River Basin in unprecedented detail, with the benefit that we will be able to discern patterns and controls on invertebrate populations that were previously impossible to describe. The publication of these data and analyses, beginning in FY15 and continuing in future fiscal years as studies are completed, thus represent a major step forward in our power to predict and describe aquatic foodbase patterns in time and space.

Finally, algae production monitoring described in Project Element 5.3 is unprecedented for a large river, and at least two peer-reviewed articles describing controls on algae production in Glen, Marble, and Grand Canyon will be produced during FY15–17.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

Aquatic ecology webpage. Provides photos and publications that describes major areas of research. (http://www.gcmrc.gov/research_areas/food_base/food_base_default.aspx)

Citizen Science in Grand Canyon. 7 minute video that describes the ecology of the Colorado River in Grand Canyon, and how citizen science insect monitoring is leading to a deeper understanding of this unique ecosystem. (http://www.youtube.com/watch?v=2TxLWlrw7y4)

E.2. Completed Publications

Cross, W.F., Baxter, C.V., Rosi-Marshall, E.J., Hall, R.O., Kennedy, T.A., Donner, K.C., Wellard Kelly, H.A., Seegert, S.E.Z., Behn, K.E., and Yard, M.D., 2013, Food-web dynamics in a large river discontinuum: Ecological Monographs, v. 83, no. 3, p. 311–337.

Kennedy, T.A., 2013, Identification and evaluation of scientific uncertainties related to fish and aquatic resources in the Colorado River, Grand Canyon—summary and interpretation of an expert-elicitation questionnaire: US Geological Survey Scientific Investigations Report 2013–5027.

Kennedy, T.A., Cross, W.F., Hall, R.O., Baxter, C.V., and Rosi-Marshall, E.J., 2013, Native and nonnative fish populations of the Colorado River are food-limited—evidence from new food web analyses: US Geological Survey Fact Sheet 2013–3039, 8 p.

Kennedy, T., Kortenhoeven, E., and Fritzinger, C., 2013, Guides + science = citizen science: Boatman's Quarterly Review, v. 26, no. 1, p. 20–21.

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E.3. Publications in progress

Clay, P.A., Muehlbauer, J.D., and Doyle, M.W., In review, Effect of tributary and braided confluences on aquatic macroinvertebrate communities and geomorphology in an alpine river watershed: Submitted to Freshwater Science.

Copp, A.J., Kennedy, T.A., and Muehlbauer, J.D. In review, Barcodes are a useful tool for labeling and tracking ecological samples: Submitted to Bulletin of the Ecological Society of America.

Hall, R.O., Yackulic, C.B., Kennedy, T.A., Yard, M.D., Rosi-Marshall, E.J., Voichick, N., Behn, K.E., In review, Turbidity, light, and hydropeaking control gross primary production in the Colorado River, Grand Canyon: Submitted to Limnology and Oceanography.

Muehlbauer, J.D., and Doyle, M.W. (In Prep) Flooding decouples a major aquatic-terrestrial subsidy: insights from the combination of multiple ecological theories: For Journal of Animal Ecology.

Muehlbauer, J.D., Clay, P.A., Doyle, M.W., and Tockner, K. (In Prep) Geophysical controls on the spatial dynamics of river-to-land subsidies, based on global field analysis: For Ecological Monographs.

E.4. Presentations at GCDAMP meetings

Kennedy, T.A., 2013, Foodbase update, Glen Canyon Dam Adaptive Management Program Technical Work Group Annual Reporting Meeting, Phoenix, Arizona, USA.

Kennedy, T.A., and Hall, R.O., 2013, Foodweb analysis shows that food availability for fish downstream of Glen Canyon Dam is severely limited, Webex Briefing to the Assistant Secretary for Water and Science.

Kennedy, T.A., Hall, R.O., and Cross, W.F., 2013, Foodweb analysis shows that food availability for fish downstream of Glen Canyon Dam is severely limited, Webex Briefing to the Technical Work Group.

Kennedy, T., Muehlbauer, J., and Yackulic, C. 2014, Foodweb update, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Arizona, USA.

E.5. Presentations at professional meetings

Copp, A.J., Kennedy, T.A., and Muehlbauer, J.D., 2013, Learning from retailers: barcoding is a useful tool for labeling and tracking samples in field and lab settings, 12th Biennial Conference of Science and Management on the Colorado Plateau: Flagstaff, Arizona, USA.

Copp, A.J., Kennedy, T.A., and Muehlbauer, J.D., 2014, Don't get clogged up: using net filtration efficiency to inform deployment length in drift studies, Joint Aquatic Sciences Meeting: Portland, Oregon, USA.

Kennedy, T., Yackulic, C., Cross, W., Grams, P., Yard, M., and Copp, A. 2013, The relationship between invertebrate drift and two primary controls—discharge and benthic density—in a large regulated river, Ecological Society of America Meeting: Minneapolis, Minnesota, USA.

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Muehlbauer, J.D., Kennedy, T.A., Smith, J.T., Sankey, J.B., and Kortenhoeven, E.W., 2014, Advances in emergent insect sampling: new sticky trap designs and automated sample processing, Joint Aquatic Sciences Meeting: Portland, Oregon, USA.

Smith, J.T., Kennedy, T.A., and Muehlbauer, J.D., 2013, Building a better bug trap, 12th Biennial Conference of Science and Management on the Colorado Plateau: Flagstaff, Arizona, USA.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY15							
							5	**Food Base Monitoring and Research**		**$470,900**	**$22,200**	**$37,100**	**$58,000**	**$36,100**	**$18,800**	**$93,000**	**$736,100**
							5.1	**Are aquatic insect diversity and production recruitment limited?**		$0	$0	$0	$0	$0	$0	$0	$0
X							5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$80,500	$400	$9,000	$3,800	$9,000	$0	$14,900	$117,600
				X			5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$47,500	$700	$3,000	$26,600	$6,800	$0	$12,400	$97,000
				X			5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$25,200	$400	$0	$0	$0	$0	$4,000	$29,600
				X			5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$25,200	$400	$0	$0	$0	$0	$4,000	$29,600
				X			5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$12,600	$700	$3,000	$0	$6,800	$0	$2,800	$25,900
				X			5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$25,200	$700	$6,000	$0	$0	$0	$5,000	$36,900
				X			5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$39,500	$1,400	$6,000	$3,800	$0	$0	$7,900	$58,600
				X			5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$12,600	$2,500	$3,000	$3,800	$0	$0	$3,400	$25,300

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY15							
							5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**		$0	$0	$0	$0	$0	$0	$0	$0
X							5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$36,400	$7,000	$1,500	$0	$0	$0	$7,000	$51,900
X							5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$72,800	$1,000	$1,500	$0	$0	$0	$11,800	$87,100
				X			5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$9,100	$300	$300	$0	$0	$9,400	$1,500	$20,600
				X			5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$9,100	$400	$300	$0	$0	$9,400	$1,500	$20,700
				X			5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$54,600	$5,300	$1,500	$20,000	$0	$0	$12,700	$94,100
							5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**		$0	$0	$0	$0	$0	$0	$0	$0
X							5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,400	$0	$0	$0	$13,500	$0	$2,000	$25,900
X							5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$10,200	$1,000	$2,000	$0	$0	$0	$2,100	$15,300
		X					5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0

Monitoring		Research															
Core activities	**Support implementation and evaluation of HFE Protocol and Non-Native Fish Control**	**Technical and analytical innovations in monitoring**	**Improving predictive modeling capacity**	**Resolving scientific uncertainty**	**Independent science oversight and review**	**Integrating tribes in monitoring and research**	**Project Identifier**	**Project Description**		**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Coop-erators (non-USGS)**	**USGS Coop-erators**	**USGS/SBSC Burden**	**Total**
									FY16								
							5	**Food Base Monitoring and Research**		**$530,900**	**$22,600**	**$38,200**	**$59,800**	**$78,500**	**$19,400**	**$141,400**	**$890,800**
							5.1	**Are aquatic insect diversity and production recruitment limited?**									
X							5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$83,300	$400	$9,300	$3,900	$1,900	$0	$20,700	$119,500
				X			5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$49,300	$700	$3,100	$27,500	$7,000	$0	$17,400	$105,000
				X			5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$26,100	$400	$0	$0	$0	$0	$5,700	$32,200
				X			5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$26,100	$400	$0	$0	$0	$0	$5,700	$32,200
				X			5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$13,000	$700	$3,100	$0	$7,000	$0	$3,800	$27,600
				X			5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$26,100	$700	$6,200	$0	$0	$0	$7,000	$40,000
				X			5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$40,800	$1,400	$6,200	$3,900	$500	$0	$11,200	$64,000
				X			5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$13,000	$2,500	$3,100	$3,900	$0	$0	$4,800	$27,300

Monitoring		Research															
Core activities	**Support implementation and evaluation of HFE Protocol and Non-Native Fish Control**	**Technical and analytical innovations in monitoring**	**Improving predictive modeling capacity**	**Resolving scientific uncertainty**	**Independent science oversight and review**	**Integrating tribes in monitoring and research**	**Project Identifier**	**Project Description**		**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Coop-erators (non-USGS)**	**USGS Coop-erators**	**USGS/SBSC Burden**	**Total**
										FY16							
							5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**									
X							5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$46,400	$7,200	$1,500	$0	$0	$0	$11,800	$66,900
X							5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$92,800	$1,000	$1,500	$0	$0	$0	$20,300	$115,600
				X			5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$11,600	$300	$300	$0	$0	$9,700	$2,600	$24,500
				X			5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$11,600	$400	$300	$0	$0	$9,700	$2,600	$24,600
				X			5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$69,600	$5,500	$1,500	$20,600	$48,200	$0	$22,200	$167,600
							5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**									
X							5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,500	$0	$0	$0	$13,900	$0	$2,700	$27,100
X							5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$10,700	$1,000	$2,100	$0	$0	$0	$2,900	$16,700
		X					5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0

Monitoring		Research															
Core activities	**Support implementation and evaluation of HFE Protocol and Non-Native Fish Control**	**Technical and analytical innovations in monitoring**	**Improving predictive modeling capacity**	**Resolving scientific uncertainty**	**Independent science oversight and review**	**Integrating tribes in monitoring and research**	**Project Identifier**	**Project Description**		**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Coop-erators (non-USGS)**	**USGS Coop-erators**	**USGS/SBSC Burden**	**Total**
									FY17								
							5	**Food Base Monitoring and Research**									
							5.1	**Are aquatic insect diversity and production recruitment limited?**		**$635,300**	**$23,300**	**$39,400**	**$61,500**	**$66,500**	**$20,000**	**$210,000**	**$1,056,000**
X							5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$93,500	$400	$9,500	$4,000	$1,400	$0	$29,400	$138,200
				X			5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$54,500	$700	$3,200	$28,300	$7,200	$0	$24,000	$117,900
				X			5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$29,400	$400	$0	$0	$0	$0	$8,200	$38,000
				X			5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$29,400	$400	$0	$0	$0	$0	$8,200	$38,000
				X			5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$14,700	$700	$3,200	$0	$7,200	$0	$5,300	$31,100
				X			5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$29,400	$700	$6,400	$0	$0	$0	$10,000	$46,500
				X			5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$45,900	$1,500	$6,400	$4,000	$1,000	$0	$15,900	$74,700
				X			5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$14,700	$2,600	$3,200	$4,000	$0	$0	$6,700	$31,200

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY17							
							5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**									
X							5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$60,400	$7,400	$1,600	$0	$0	$0	$19,000	$88,400
X							5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$120,800	$1,100	$1,600	$0	$0	$0	$33,800	$157,300
				X			5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$15,100	$300	$300	$0	$0	$10,000	$4,300	$30,000
				X			5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$15,100	$400	$300	$0	$0	$10,000	$4,300	$30,100
				X			5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$90,600	$5,600	$1,600	$21,200	$49,700	$0	$34,100	$202,800
							5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**									
X							5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,600	$0	$0	$0	$0	$0	$2,900	$13,500
X							5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$11,200	$1,100	$2,100	$0	$0	$0	$3,900	$18,300
		X					5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0

Project 6. Mainstem Colorado River Humpback Chub Aggregations and Fish Community Dynamics

Initiall Estimate: FY15: $567,600; FY16: $626,200; FY17: $733,800

GCDAMP Funding: FY15: $567,600; FY16: $582,400; FY17: $697,100

Other BoR Funding: FY15: $102,700; FY16: $66,900; FY17: $0

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B. Project Summary

Native and nonnative fish populations in Glen and Grand Canyons are key resources of concern influencing decisions on both the operation of Glen Canyon Dam and non-flow actions. To inform these decisions, it is imperative that accurate and timely information on the status of fish populations, particularly the endangered humpback chub (*Gila cypha*), be available to managers. A suite of adaptive experimental management actions are either underway or being contemplated to better understand the mechanisms controlling the population dynamics of fish in the Colorado River in Glen and Grand Canyons and to identify policies that are consistent with the attainment of management goals. Much effort has been and continues to be focused on humpback chub and rainbow trout (*Oncorhynchus mykiss*) both in the reach of the Colorado River from Glen Canyon Dam to the Little Colorado River (LCR) confluence and in the LCR itself (see Projects 7 and 9). While this work is important and meets critical information needs, it is also important to have robust monitoring of mainstem fish populations downstream of the LCR confluence. Status and trend information is needed to further understand mechanisms controlling native and nonnative fish population dynamics, determine the effects of dam operations and other management actions, and identify evolving threats presented by expansion in range or numbers of nonnative predators. This type of information is also potentially useful in assessing changes to the Federal Endangered Species Act listing status of humpback chub in Grand Canyon.

Sampling mainstem humpback chub aggregations has been conducted periodically over the last two decades. Fish were sampled by hoop and trammel nets at aggregations first described by Valdez and Ryel (1995). Most captures of humpback chub in the mainstem Colorado River have been downstream of the LCR (Persons and others, *in preparation*). Continuing to sample for humpback chub in the mainstem river outside of the LCR and the LCR confluence area is important for monitoring the status of the Grand Canyon population of this endangered species and determining the effects of management actions like dam operations and translocations.

During the last few years the first 75 miles of the Colorado River downstream of Glen Canyon Dam has been sampled extensively for fish by several projects including the following projects in the USGS Grand Canyon Monitoring and Research Center's (GCMRC) FY11–12 and FY13–14 work plans:

- **E.2** Juvenile Chub Monitoring Project near the LCR confluence Near Shore Ecology Project; BIO 2.R15.11 in FY11–12; and Project Element F.3 in FY13–14,
- **H.2** Rainbow Trout Movement Project, a.k.a. the Rainbow Trout Natal Origins Project; Project Element BIO 2.E18 in FY11–12; and Project Element F.6 in FY13–14,
- **D.4** System Wide Electrofishing Projectl; Project Element BIO 2.M4 in FY11–12; and Project Element F.1 in FY13–14
- **H.1** Lees Ferry Trout Monitoring Project; Project Element BIO 4.M2 in FY11–12; and Project Element F.2 in FY13–14
- **D.7** Rainbow Trout Early Life Stage Survey Project; RTELSS, Project Element BIO 4.M2 in FY11–12; and Project Element F.2.2 in FY13–14

The remaining portion of the Colorado River downstream of Glen Canyon Dam (between approximately the LCR and Lake Mead) has been sampled using standardized methods since 2000 as described in Project 6.4, the System Wide Electrofishing Project and since 2010 as described in Project 6.1, the Mainstem Humpback Chub Aggregation Monitoring Project. In order to improve efficiencies and to reduce duplication of effort, GCMRC and cooperating agencies conducting fisheries monitoring and research propose to coordinate and/or combine several project elements in GCRMC's FY15–17 work plan. These include the Juvenile Chub Monitoring project and System Wide Electrofishing effort (see Project Elements 7.2 and 6.4) as well as the Rainbow Trout Natal Origins study and Lees Ferry Trout Monitoring (see Project Elements 9.1 and 9.2). In general, this will mean a reduction of electrofishing effort in the first 70 miles of the Colorado River downstream of Glen Canyon Dam and a focus on obtaining abundance estimates rather than catch per unit effort (CPUE) indices through the updated Lees Ferry Rainbow Trout Monitoring project (see Project Elements 9.1 and 9.2). Systematic sampling of the mainstem Colorado River downstream of the Juvenile Chub Monitoring (see Project Element 7.2) reference site (River Mile (RM) 63-64.5) will continue under Project Elements 6.1, 6.2, and 6.4 (see Section 4) and will continue to collect and analyze species composition and CPUE data.

Project 6 is comprised of eight Project Elements and includes monitoring and research projects in the mainstem Colorado River, with particular emphasis on humpback chub aggregations. Over the last several years humpback chub in the LCR aggregation have increased in abundance (Coggins and Walters, 2009; Van Haverbeke and others, 2013; Yackulic and others, 2014). Humpback chub at many other aggregations have also increased in abundance, and some aggregations appear to have increased their distribution (Persons and others, *in preparation*). Recruitment to aggregations may come from local reproduction (e.g. 30 Mile aggregation; Andersen and others, 2010; Middle Granite Gorge Aggregation; Douglas and Douglas, 2007), the LCR aggregation, and translocations to Shinumo and Havasu Creeks.

Annual monitoring of the status and trends of the mainstem humpback chub aggregations has been identified as a conservation measure in a recent Biological Opinion (U.S. Fish and Wildlife Service, 2011) and will continue to be monitored in Project Element 6.1, although effort will be reduced to a single trip per year down from two trips annually in the FY13–14 work plan. We will also continue to sample in conjunction with the National Park Service (NPS) near Shinumo Creek and Havasu Creek to assess contribution of translocated humpback chub to mainstem aggregations.

Understanding recruitment at aggregations continues to be an area of uncertainty. Humpback chub otolith microchemistry (Hayden and others, 2012; Limburg and others, 2013) was proposed as a method to determine sources of humpback chub recruitment in the FY13–14 Work Plan. However, due to Tribal concerns about directed take of humpback chub we were unable to collect the otoliths necessary for these analyses. During FY15–16 we plan to further evaluate the use of otolith microchemistry to identify surrogate fish hatched in Shinumo Creek, Havasu Creek, 30-Mile springs or other locations in Project Element 6.2. We will work with NPS staff to collect water samples and otoliths from brown trout (*Salmo trutta*), rainbow trout, and other fishes sacrificed as part of their trout removal activities. We will also make use of any humpback chub incidentally killed during other sampling efforts. Further, we will place additional emphasis on catching and marking juvenile humpback chub to assist in determining sources of recruitment to aggregations. During FY15–16 we propose to evaluate slow shocking and seining as methods to capture and mark more juvenile humpback chub with passive integrated transponder (PIT) tags in order to assess juvenile humpback chub survival and recruitment to aggregations. This will also provide a possible method to assess dispersal of juvenile humpback chub marked in the LCR with visible implant elastomer (VIE) and PIT tags (see Project Element 7.3).

Project Element 6.3 will continue efforts that began in the FY13–14 work plan to locate additional aggregations by standardized sampling and by the use of remotely deployed PIT-tag antennas. GCMRC has had success in deploying relatively portable PIT-tag antennas in the LCR and proposes to work with NPS and U.S. Fish and Wildlife Service (USFWS) personnel to develop antenna systems that can be deployed at mainstem aggregations and other locations to detect PIT-tagged fish. If successful, these systems will provide an opportunity for collaborative citizen science with commercial and scientific river trips whereby river guides could deploy antennas overnight at camp sites in an attempt to detect PIT-tagged fish in areas not sampled during mainstem fish monitoring trips.

The System Wide Electrofishing Project (Project Element 6.4) will continue to collect long-term monitoring data following the methods described in Makinster and others, (2010) and will evaluate the efficacy of a mark-recapture approach downstream of the LCR confluence. To eliminate duplicative efforts, we propose that sampling be conducted in areas not sampled by the Rainbow Trout Natal Origins and the Juvenile Chub Monitoring projects (Project Elements 7.2

and 9.2). We will also increase sampling effort downstream of Diamond Creek to monitor for native and non-native fishes. Continued concerns over upstream movement of non-native warmwater predatory species such as striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*) and walleye (*Sander vitreus*) from Lake Mead highlight the need to continue to monitor the river for non-native fishes. Electrofishing is effective at capturing bass species, sunfishes (Centrarchidae), and walleye, so this sampling should detect upstream movements of these species. Channel catfish on the other hand, are not effectively captured by electrofishing, so monitoring of catfish distribution by standardized angling (Persons and others, 2013) will continue during electrofishing trips. Standardized electrofishing sampling is also effective at capturing native sucker species including flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and razorback sucker (*Xyrauchen texanus*). Recent captures of razorback sucker downstream of Diamond Creek by this project have been widely publicized and ongoing monitoring will help document if this once extirpated species continues its apparent re-colonization of Grand Canyon.

Nonnative brown trout are effective fish predators known to preferentially prey on native Colorado River fishes including humpback chub (Yard and others, 2011). Determining the source or sources of this species in Grand Canyon will help scientists and managers better target efforts aimed at controlling this threat to native fish populations (see Project Element 8.1). Project Element 6.5 will conduct research on the use of brown trout pigment patterns to identify natal origins of brown trout; data and images will be collected during the System Wide Electrofishing Project and other projects that encounter brown trout.

One risk to the Grand Canyon humpback chub population is that it includes only one self-sustaining spawning population, the LCR aggregation. The USFWS has identified the establishment of a second self-sustaining spawning population of humpback chub as an important step towards recovery of this endangered species (U.S. Fish and Wildlife Service 1995). Project Element 6.6 will develop plans and conduct necessary compliance activities to experimentally translocate humpback chub from the LCR to a mainstem aggregation in 2016 or later.

The Rainbow Trout Early Life Stage Survey (Project Element 6.7 - RTELLS) seasonally monitors rainbow trout egg deposition and population early life history dynamics, particularly age-0 survival in Glen Canyon. This project in particular, provides managers with an initial indication of the annual cohort strength of rainbow trout recruiting into the population. Findings from this also have relevance to the Natal Origin research project (see Project Element 9.2).

The Lees Ferry Creel Survey (Project Element 6.8) monitors the health of the rainbow trout fishery and provides information on the influence of Glen Canyon Dam operations, other management actions, and natural disturbances on recreational fishing. Information on the levels of direct harvest as well as angler use and satisfaction of the important recreational fishery is also provided.

C. Background

C.1 Scientific Background

Currently, the only known reproducing and self-sustaining population of humpback chub within Grand Canyon is in the LCR and in the mainstem Colorado River near its confluence with the LCR (Valdez and Ryel, 1995; Gloss and Coggins, 2005; Coggins and others, 2006). Because these fish appear to rely exclusively on the LCR for reproduction, they are at increased risk of catastrophic loss (U.S. Fish and Wildlife Service, 2008; Bureau of Reclamation, 2011).

Eight other aggregations of humpback chub were described in the mainstem Colorado River (Valdez and Ryel, 1995), and closed population model abundance estimates were generated for six of those aggregations An aggregation was defined as “a consistent and disjunct group of fish with no significant exchange of individuals with other aggregations, as indicated by recapture of PIT-tagged juveniles and adults and movement of radio-tagged adults” (Valdez and Ryel, 1995). Recent data collected at aggregations and throughout the Colorado River, suggest that there is substantial movement among some of the originally identified aggregations, and they may not all meet the original definition of an aggregation.

The LCR aggregation of humpback chub has been studied extensively, (Van Haverbeke and others, 2013; Yackulic and others, 2014) and models have been developed to estimate abundance of chub in the LCR and near the confluence of the Colorado River (Coggins and Walters, 2009; Yackulic and others, 2014). Results from these efforts demonstrate that humpback chub abundance in the LCR aggregation has increased over the last several years (Coggins and Walters, 2009; Van Haverbeke and others, 2013; Yackulic and others, 2014). An understanding of the status and trends of humpback chub outside of the LCR population is needed for managers to assess the effects of Glen Canyon Dam operations on mainstem populations of humpback chub. Recent findings suggest that humpback chub relative abundance has increased at most locations since the 1990’s and some aggregations appear to have increased their distribution (fig. 1) (Persons and others, *in preparation*).

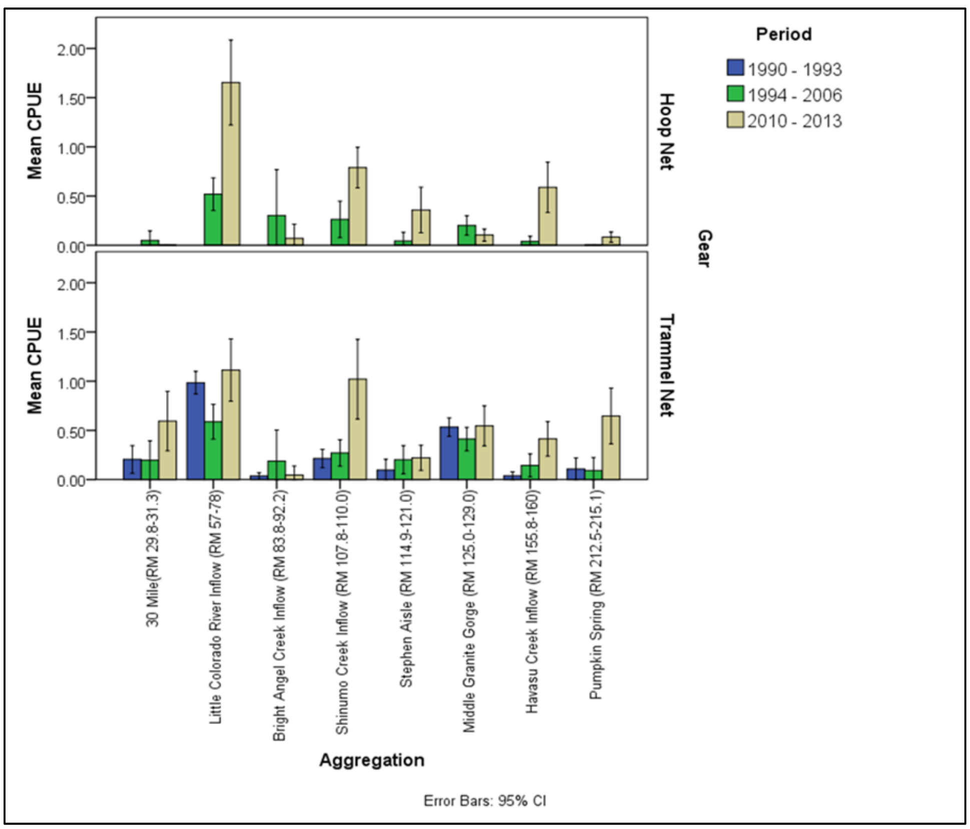
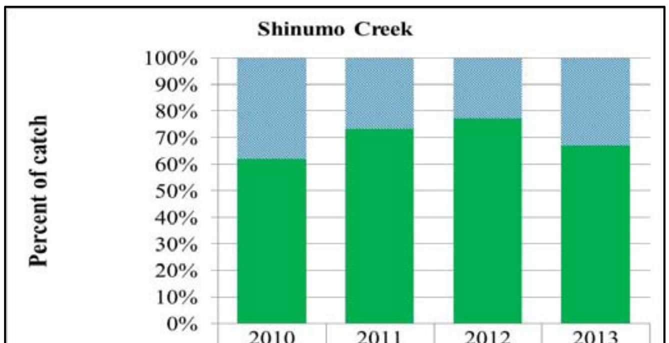


Figure 1. Mean catch per unit effort (CPUE) in humpback chub ≥ 150 mm TL per 24 hours for hoop net and humpback chub ≥ 150 mm TL per 2 hours for trammel nets at eight humpback chub aggregations, 1990-2013. Error bars represent 95% confidence intervals of the mean (Persons and others, *in prep*).

Recruitment to aggregations may come from local reproduction (e.g., 30 Mile aggregation; Andersen and others, 2010; Middle Granite Gorge Aggregation; Douglas and Douglas, 2007), the LCR aggregation, and translocations to Shinumo and Havasu Creeks. Recent evidence indicates that female humpback chub are capable of producing eggs at most aggregations (M. Brizendine, GCMRC Annual Reporting Meeting 2014 poster). In addition, humpback chub that were translocated to Shinumo and Havasu Creeks are common in catches near the confluences of these two tributaries (fig. 2) (Persons and others, in prep).



	2010	2011	2012	2013
Not Translocated	14	13	7	20
Translocated	23	36	24	41

Figure 2. Number and percent of humpback chub captured during aggregation sampling trips that were previously translocated to Shinumo Creek (Persons and others, *in prep*).

Valdez and Ryel (1997) were able to generate closed abundance estimates of humpback chub at several aggregations by sampling up to 7 times per year. The amount of sampling required to generate similar abundance estimates raises serious concerns about over-handling these rare fish. From a conservation standpoint, it may be more hazardous to extensively sample this endangered species in order to generate abundance estimates than it is to monitor trends over time using CPUE indices.

Attempts were made to estimate humpback chub abundance at known aggregations during 2012 and 2013 using pooled capture probability estimates derived from closed mark-recapture population estimates. This approach and these estimates were deemed not valid during peer review. In addition, attempts to generate two-pass mark-recapture population estimates at the Shinumo Creek aggregation during 2012 by combining NPS sampling and USFWS/GCMRC sampling were unsuccessful because capture probabilities appeared to change dramatically between the first capture event and subsequent attempts to recapture fish within a few days. Results suggest fish were evidently very trap-shy after their initial capture.

We propose to continue use of CPUE indices to evaluate trends in relative abundance of humpback chub at known aggregations as well as at locations not associated with aggregations (Persons and others, *in preparation*). Although CPUE indices have a high degree of uncertainty, trends in these indices over 4–5 year time periods are likely reflective of relative abundance of humpback chub in the mainstem Colorado River. Use of CPUE indices to evaluate changes in abundance over annual time periods is not proposed due to the high variability in capture probabilities (the probability of capturing an individual fish) among trips.

Limburg and others (2013) developed a geochemical atlas of the Colorado River in Grand Canyon and in the Little Colorado River, and used it to identify provenance and habitat use by humpback chub. We had planned to evaluate use of similar techniques using carbon stable isotope ratios (δ^{13} C) and other tracers (SrSr, Ba, and Se in ratio to Ca) to learn the natal origins of humpback chub collected in the mainstem Colorado River distant from the LCR, but were not able to collect fish due to tribal concerns. We plan to expand the humpback chub otolith microchemistry project to include other tributaries and springs, and to use brown trout and rainbow trout from Shinumo, Havasu and Bright Angel Creeks as surrogate species to determine if they reveal unique markers from different tributaries.

Long-term fish monitoring in the mainstem Colorado River has been an essential element of GCDAMP supported fisheries work. Data from this program provides managers and stakeholders with accurate and timely information on the status and trends of fish populations in Grand Canyon in support of their efforts manage Glen Canyon Dam operations and other non-flow actions in a manner beneficial to the aquatic ecosystem. The annual System Wide Electrofishing (SWEF) of native and nonnative fish in the mainstem Colorado River has been ongoing since 2000 (Makinster and others, 2010). These efforts rely upon boat-operated electrofishing to provide information on native and nonnative fishes between Lees Ferry and Lake Mead. Information generated includes population status and trends and species distributions as well as surveillance for undesirable or potentially harmful nonnative species (figs. 3, 4).

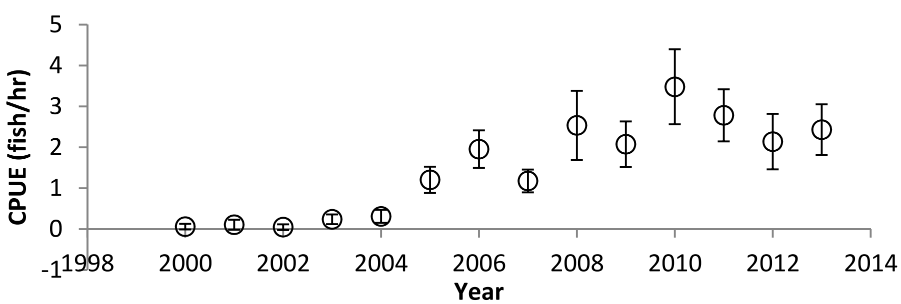


Figure 3. Mean river-wide CPUE (catch per hour) of bluehead sucker captured during sampling in the Colorado River, Grand Canyon, AZ, 2000 – 2013. Error bars represent 95% confidence intervals. Note: the number of sample sites differs from year to year (Rogowski and others, 2014a).

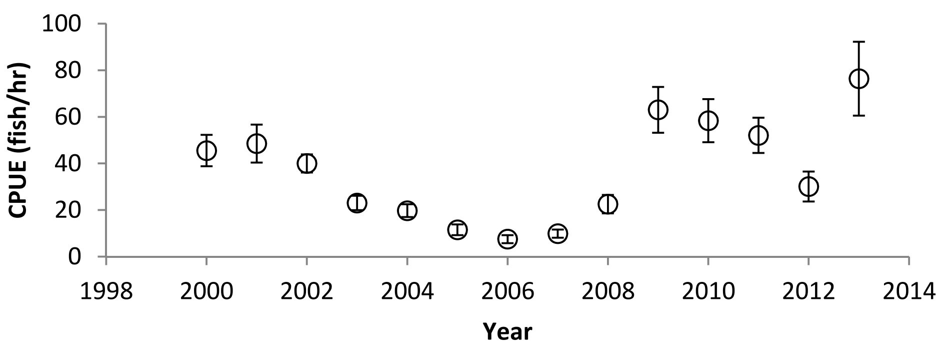


Figure 4. Mean river-wide CPUE (catch per hour) of rainbow trout captured during sampling in the Colorado River, Grand Canyon, Ariz., 2000–2013. Error bars represent 95% confidence intervals. Note: the number of sample sites differs from year to year (Rogowski and others, 2014b).

Surveys of anglers in the Lees Ferry tailwater reach have been conducted by the Arizona Game and Fish Department. Angler catch, effort, and harvest data have been collected regularly since 1966 (Persons and others 1985, Reger and others 1998) and data has been used to recommend changes in regulations and management strategies. Creel data provide a good index of angler satisfaction, and catch rate of rainbow trout (fish per hour) is well correlated with electrofishing catch per minute (Rogowski and others, 2014b) (fig. 5).

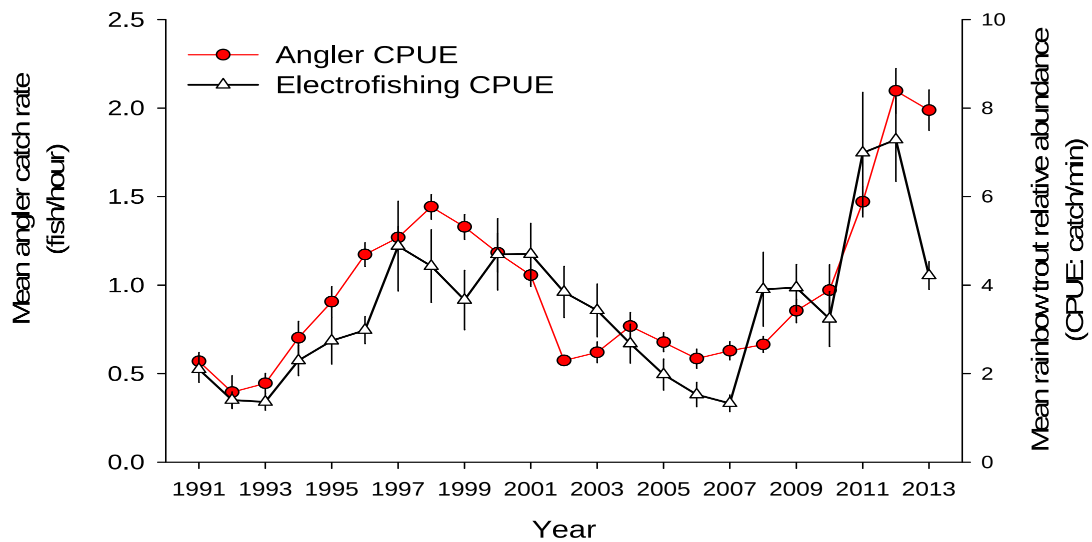


Figure 5. Comparison of rainbow trout mean CPUE from two methods, standard boat electrofishing and angler surveys of boaters at Lees Ferry boat ramp, Colorado River, error bars are 95% confidence intervals (Rogowski and others, 2014b).

GCMRC has developed and maintained a database of all known fish capture records from Grand Canyon starting in the early 1980's. Although effort and types of gear have changed over time, there are some general patterns in distribution of many warmwater nonnative piscivores, with fish more common in the tailwater below Glen Canyon Dam and in western Grand Canyon near the inflow to Lake Mead (fig. 6). Walleye, striped bass, smallmouth bass, and largemouth bass are found in both Lake Powell and Lake Mead. Large (> 400 mm TL) walleye were captured downstream from Diamond Creek by trammel net in the early 1990's when Bio/West sampled western Grand Canyon intensively (Valdez and Ryel, 1996) and more recently by AGFD electrofishing downstream of Diamond Creek (Rogowski and others, 2014a) . Large walleye have also been captured by electrofishing just below Glen Canyon Dam near the right spillway during nonnative surveillance surveys (Rogowski and others, 2014b). These fish most likely came from Lake Powell through the Glen Canyon Dam turbines.

Large adult (> 400 mm TL) striped bass were common in trammel net catches downstream of Diamond Creek during 1993 and 1995 when Lake Mead water level was fairly high (Valdez and Ryel, 1996). Large adult striped bass were again common in catches downstream of Diamond Creek in 2006 when trammel net and electrofishing effort was higher (SWCA, unpublished data, AGFD, unpublished data), but striped bass have been relatively rare in catches since 2011. Striped bass are occasionally captured near the confluence of the Little Colorado River. They are rarely seen at the base of Glen Canyon Dam and most fish are dead and likely came through the turbines.

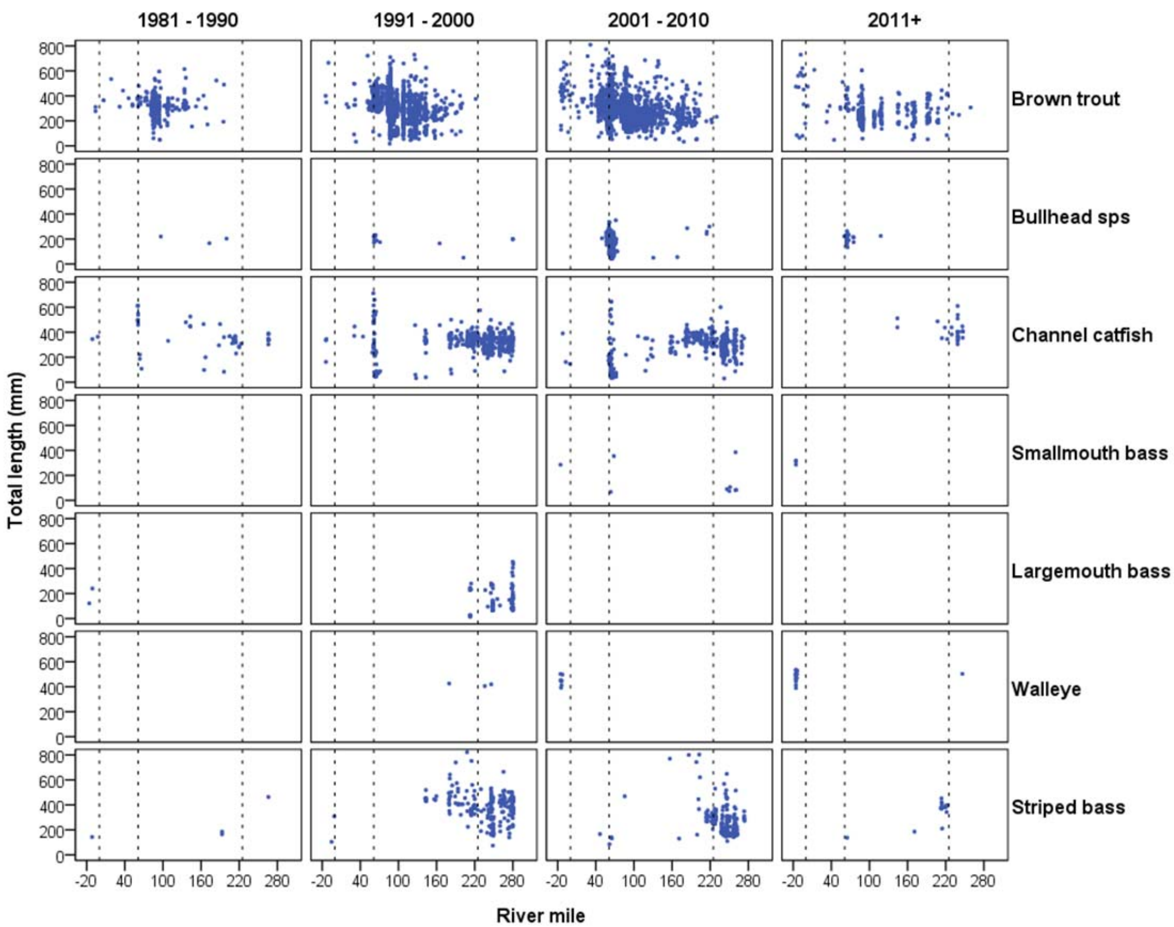


Figure 6. Catch of large bodied nonnative piscivorous fish by time period, river mile (RM), and size of fish. Each point represents an individual fish capture. Vertical dashed lines represent, from left to right, RM 0 (Lees Ferry), RM 61 (Little Colorado River), and RM 225 (Diamond Creek). Note that effort and gear types varied between periods. GCMRC unpublished data.

Smallmouth bass are known to be highly detrimental to native fish in the Upper Colorado River basin. Smallmouth bass are vulnerable to electrofishing but are rare in Grand Canyon catches (n=12) with most captured downstream of Diamond Creek. Five adult smallmouth bass (>285 mm TL) were captured in recent years during directed nonnative surveillance electrofishing near the base of Glen Canyon Dam (Rogowski and others, 2014b). Two smallmouth bass were captured near the LCR confluence by electrofishing, a 354 mm TL individual in 2005 and a 68 mm individual in 2006 (GCMRC unpublished data). Two largemouth bass were captured in the Lees Ferry tailwater in 1985 (Maddux and others, 1986), the other 75 in the GCMRC database were all captured in western Grand Canyon downstream of

RM 212.

Channel catfish were one of the most common species in Grand Canyon prior to closure of Glen Canyon Dam and comprised 90% of the fish population in Glen Canyon (AGFD, unpublished data in Niccum and others, 1998). After closure of the Dam few channel catfish have been captured in Glen and Marble Canyon, but the species is common downstream of about RM 179 (Lava Falls). Adult channel catfish are rarely captured during standard hoop net monitoring in the LCR, but are vulnerable to directed angling and there are periodic large catches of young channel-catfish in the Little Colorado River (GCMRC unpublished data). Most adult channel catfish were collected by trammel net, and the species is common downstream of Diamond Creek.

Bullheads (primarily black bullhead) are occasionally common in LCR hoop net catches, but they do not seem to persist long in the system (Stone and others, 2007) . They are rarely captured in other parts of the system.

Brown trout are found throughout most of Grand Canyon, but the center of their distribution is near Bright Angel Creek (fig. 7). Grand Canyon National Park has initiated a project to attempt to remove trout from Bright Angel Creek (Nelson and others, 2014; National Park Service, 2013), and Project element 8.1 includes evaluating the feasibility of brown trout removal using electrofishing in the mainstem Colorado River near the confluence of Bright Angel Creek in support of this effort.

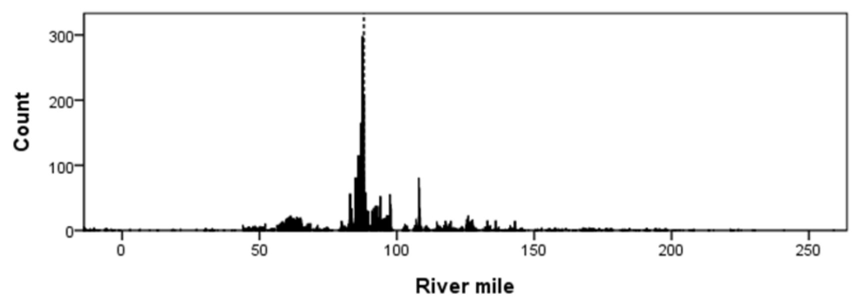


Figure 7. Number of brown trout captured by river mile, GCMRC unpublished data. Dashed line at river mile 88 represents Bright Angel Creek.

C.2. Key Monitoring and Research Questions Addressed in this project

This project directly addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) previously identified by the Glen Canyon Dam Adaptive Management Program (GCDAMP).

Primary SSQ addressed:

- **SSQ 1-1.** To what extent are adult populations of native fish controlled by production of young fish from tributaries, spawning and incubation in the mainstem, survival of young-of-year and juvenile stages in the mainstem, or by changes in growth and maturation in the adult population as influenced by mainstem conditions?
- **SSQ 1-2.** Does a decrease in the abundance of rainbow trout and other cold- and warm water nonnatives in Marble and eastern Grand Canyons result in an improvement in the recruitment rate of juvenile humpback chub to the adult population?

- **SSQ 1-8.** How can native and nonnative fishes best be monitored while minimizing impacts from capture and handling or sampling?

The GCDAMP Science Advisors articulated the following summary science questions addressed by this project:

- **SA 1.** What are the most limiting factors to successful humpback chub adult recruitment in the mainstem: spawning success, predation on young of year and juveniles, habitat (water, temperature), pathogens, adult maturation, food availability, competition?
- **SA 2.** What are the most probably positive and negative impacts of warming the Colorado River on humpback chub adults and juveniles?

Information Needs Addressed:

- **CMIN 2.1.2.** Determine and track recruitment of all life stages, abundance, and distribution of humpback chub in the Colorado River.
- **CMIN 2.4.1.** Determine and track the abundance and distribution of nonnative predatory fish species in the Colorado River.
- **CMIN 2.6.1.** Determine and track the abundance and distribution of flannelmouth sucker, bluehead sucker, and speckled dace populations in the Colorado River ecosystem.
- **RIN 2.2.8.** What combination of dam release patterns and nonnative fish control facilitates successful spawning and recruitment of humpback chub in the Colorado River ecosystem?
- **RIN 2.4.2.** Determine if suppression of nonnative predators and competitors increases native fish populations.
- **RIN 2.4.3.** To what degree, which species, and where in the system are exotic fish a detriment to the existence of native fish through predation or competition?
- **RIN 2.4.4.** What are the target population levels, body size, and age structure for nonnative fish in the Colorado River ecosystem that limit their levels to those commensurate with the viability of native fish populations?
- **EIN 2.1.1.** How does the abundance and distribution of all size classes of HBC in the LCR and mainstem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?
- **EIN 2.1.2.** How does the year class strength of HBC (51–150 mm) in the LCR and mainstem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?
- **EIN 2.4.1.** How does the abundance and distribution of nonnative predatory fish species and their impacts on native fish species in the Colorado River ecosystem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?
- **EIN 2.6.1** How does the abundance, distribution, recruitment and mortality of flannelmouth sucker, bluehead sucker and speckled dace populations in the Colorado River ecosystem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?

C.3. Key management goals and objectives addressed in this project

- **Goal 2:** Maintain or attain a viable population of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats.

In August 2004, the GCDAMP Adaptive Management Work Group reviewed these goals and identified priority questions. This project addresses the top priority question:

- **Priority 1**: Why are humpback chub not thriving, and what can we do about it? How many humpback chub are there and how are they doing?

D. Proposed Work

D.1. Project Elements

Project elements include sampling humpback chub aggregations, investigating recruitment at aggregations, investigating the use of PIT-tag antennas at aggregations, system wide monitoring of native and non-native fishes outside of Glen and Marble Canyons, investigating brown trout origins through examining their pigment patterns, investigating the translocation of humpback chub to the mainstem Colorado River, and investigating the use of portable PIT tag antennas to detect tagged humpback chub and other fishes

Project Element 6.1. Monitoring humpback chub aggregation relative abundance and distribution

William Persons, Fishery Biologist, USGS, GCMRC
D.R. Van Haverbeke, Fishery Biologist, U.S. Fish and Wildlife Service
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park

This Project Element will concentrate on monitoring status and trends of humpback chub aggregations not associated with the LCR. This Project Element will build on work conducted in 2013 and 2014. Persons and others (*in prep*) have been able to detect long term changes in relative abundances by pooling data into 5-year blocks, but were unable to provide defensible annual abundance estimates from the aggregations (Persons and others, GCMRC Annual Reporting Meeting, 2014). Sampling will be reduced from two trips to one trip, but will include sampling by seine and nearshore electrofishing which has been effective capturing juvenile humpback chub near the LCR confluence (J. Korman, *pers. comm*.). While sampling trips will concentrate on known aggregations and translocation sites, several days of effort will also be devoted to sampling areas associated with springs and faults thought likely to harbor humpback chub.

The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.2. Humpback chub aggregation recruitment studies

Michael Dodrill, USGS, GCMRC
Karin Limburg, State University of New York
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park

Recent apparent increases in relative abundance of humpback chub at mainstem aggregations (Persons and others, *in preparation*) suggest that local recruitment may be occurring at some sites. While it is known that the LCR serves as a source of humpback chub into the mainstem Colorado River and that some of these fish move downstream and survive, there may be other areas with local reproduction that act as sources of recruitment (Andersen and others, 2010). Although we will not deliberately sacrifice humpback chub to collect otoliths for microchemistry analysis, we will work with NPS to collect surrogate species from tributaries of interest and analyze samples for unique chemical signatures that might be associated with particular tributaries. We will continue to work with all projects to collect and preserve any humpback chub incidentally killed during sampling.

This Project Element will also attempt to collect juvenile humpback chub in backwaters and other nearshore areas by seining and electrofishing. Fish will be examined closely for VIE tags (see Project Element 7.3) and PIT tags to evaluate possible sources of recruitment. The project will also acquire and explore the use of a thermal imaging infrared camera to help identify sampling locations at warm springs in the mainstem.

The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.3. Monitoring mainstem humpback chub aggregations using PIT-tag antenna technology

Kirk Young, Fishery Biologist, U.S. Fish and Wildlife Service
D.R. Van Haverbeke, Fishery Biologist, U.S. Fish and Wildlife Service
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
David Ward, Fishery Biologist, USGS, GCMRC
William Persons, Fishery Biologist, USGS, GCMRC

The objective of this project is to investigate use of remotely deployed, portable PIT-tag antennas to monitor mainstem aggregations of humpback chub, especially at mainstem translocation sites. Two long standing goals of biologists monitoring humpback chub in Grand Canyon are to develop indices to monitor the abundance or relative abundance of humpback chub, and to reduce handling of fish. This project will evaluate use of stationary, temporary PIT-tag antennas to detect humpback chub and other PIT-tagged fish in the mainstem Colorado River. Deployment of antennas at known aggregations may also help answer questions about residencies of humpback chub within and among aggregations, potential gene flow among the aggregations, and movement. It is believed that given strategic placement of antennas at sites such as near Shinumo Creek, we may be able to increase the detection rates of tagged fish, and possibly decrease the amount of trammel netting or hoop netting. In addition, remote antennas could be deployed near future translocation sites in the mainstem. If proven feasible, similar technology might also be used in a Citizen Science approach working with commercial and science river guides to deploy PIT-tag antennas at overnight campsites.

Investigators and involved agencies will coordinate selection of appropriate locations, obtain environmental clearances, coordinate with tribes and install up to three experimental remote solar powered PIT-tag antennas at known aggregations. Site location, materials, and temporary installation strategies will be deployed so as to minimize visual impact and Grand Canyon visitor detection. Possible sites include near aggregations at 30-Mile, the Shinumo Creek Inflow, Middle Granite Gorge, the Havasu Creek Inflow, or near RM 214. Sites for antennas would be located at aggregations that have historically yielded a high number of chub. The ability to keep antennae equipment safe and out of view of the public would also be a factor in site selection. Antennas will be downloaded and serviced from existing GCMRC river trips and data will be evaluated for incorporation into the GCRMC fish database. The project will produce annual progress reports and recommendations for use of the methods and data as part of long-term monitoring efforts.

Project Element 6.4. System Wide Electrofishing

David Rogowski, Fishery Biologist, Arizona Game and Fish Department
William Persons, Fishery Biologist, USGS, GCMRC

The primary objective of this project element is to continue providing data on the longitudinal distribution and status of the fish community in the mainstem Colorado River from Lees Ferry to Lake Mead, with an emphasis on reaches downstream of Lava-Chuar rapid (RM 66.0). This project uses CPUE indices to track relative status and trends of the most common native and nonnative fish species in the mainstem. The current monitoring program was designed to be able to detect population level changes in target species over a five-year time scale. Localized questions or questions on a time scale shorter than five years require additional, separate effort beyond that outlined for long-term monitoring (Rogers and others, 2008). Given this, we propose to incorporate mark-recapture sampling events to estimate fish abundance and vital rates at specific sites (e.g., confluence of Bright Angel Creek, reaches downstream of Diamond Creek) to evaluate the ability of this approach to address questions of interest to scientists and managers.

Sampling for the SWEF project in FY13–14 consisted of two annual spring electrofishing trips from Lees Ferry to Diamond Creek and one fall trip from Diamond Creek to Lake Mead. For the FY15–17 workplan, we propose to increase sampling effort by extending one spring trip to include sampling from Diamond Creek to Lake Mead. This will extend the temporal and geographic scope of available information on nonnative and native fish in this reach of the Colorado River. In order to avoid duplication of effort with the Natal Origins research project (Project Element 9.2), we propose to coordinate sample site selection such that these projects avoid sampling in the same reaches. Stratified random sampling will occur in Marble Canyon, but at a reduced effort and may occur in directed areas of interest not sampled by the Natal Origins research project (e.g., near the confluence of Nankoweap Creek). To avoid oversampling and duplication of effort, sampling will not occur in the Juvenile Chub Monitoring (see Project Element 7.2) reference site (RM 63-64.5). Normal random stratified sampling will occur from Lava-Chuar rapid (RM 66.0) to Lake Mead and will provide information on species composition and relative abundance.

Difficulties arise in fish monitoring programs as a result of the rarity of many species, life history characteristics that contribute to patchy distributions and variable densities in time and space, low and variable capture probabilities, and the inability to use consistent sampling gear among all occupied habitats. With the exception of mark-recapture based abundance estimators, most fish monitoring efforts produce relative indices of abundance (e.g., catch rates, presence/absence) for monitoring the status and trend of a fish community. Yet, in order for catch rates (i.e., CPUE) to be effective as a short term monitoring metric, capture probabilities (probability of an animal being caught) need to be known rather than just assumed to be constant across sites or sampling periods. When capture probabilities vary due to factors like trout densities, fish size or turbidity levels (Korman and others, 2009; Korman and others, unpublished data; Speas and others, 2004), catch rate indices can become an inaccurate proxy for fish abundance. Factors like these are a common phenomenon in Grand Canyon that leads to estimation biases in fish abundance. For example, catch rates are likely to underestimate actual abundance at high trout densities (i.e., Glen Canyon) and overestimate actual abundance under low trout densities (i.e., below the LCR). Therefore, reliance on this type of metric solely becomes problematic, particularly when management decisions require a high degree of accuracy. This can only be resolved if capture probabilities are estimated using mark-recapture procedures, hence our interest in implementing this approach at selected sites to address specific questions.

For FY15–17, we propose a hybrid approach be evaluated for this project; one that maintains continuity with past SWEF sampling, but also evaluates the applicability of using a mark-recapture program (where increased accuracy and precision are needed), particularly in the downstream reaches. One downstream sampling trip and part of the second will use the standard SWEF sampling (single-pass) protocol with a stratified random sampling design used in site selection (400-500 sites per year) (similar to Makinster and others, 2010). The second downstream sampling trip will also incorporate one or more focused mark-recapture efforts using similar sampling protocols developed for the Natal Origin research project (Korman and others, 2012) at specific areas of interest (e.g., confluence of Bright Angel Creek, reaches downstream of Diamond Creek). This may require lengthening the duration of the second trip by several days to implement both sampling protocols. Data from initial efforts will be used in conjunction with other mark-recapture and CPUE data to develop a set of estimation procedures for conducting simulations to evaluate and redesign the GCDAMP's long-term fishery monitoring programs inclusive of the System Wide Electrofishing program. The redesigned program will be evaluated by an independent protocol evaluation panel (see Project Element 8.3). Sampling efforts as part of the System Wide Electrofishing program will continue sampling the downstream sections including below Diamond Creek. Three trips will be conducted annually during late April-May, late May-June, and October (Diamond Creek to Pearce Ferry) to increase the probability that maximum water clarity conditions are present for electrofishing, particularly in the downstream reaches.

This project will produce trip and annual reports with recommendations for long-term monitoring.

Project Element 6.5. Brown trout natal origins through body pigmentation patterns in the Colorado River

David Rogowski, Fishery Biologist, Arizona Game and Fish Department, Research Branch
Michael Collyer, Assistant Professor, Western Kentucky University
William Persons, Fishery Biologist, USGS, GCMRC

Non-native brown trout have been introduced into the Colorado River and tributaries and are maintaining a naturally reproducing population. Brown trout are highly piscivorous and negatively affect the imperiled native fishes of the Colorado River drainage (Yard and others, 2011). Much effort has been invested in control and removal of brown trout and other non-natives (Coggins and others, 2011; Yard and others, 2011). It is thought that the bulk of reproduction and recruitment occurs in the tributaries (e.g., Bright Angel Creek). However, it is not known whether Bright Angel Creek is the main source of brown trout into the system, if there are other major recruitment areas (mainstem or tributaries), or even if there is a large panmictic population or a number of smaller populations. For salmonids there appears to be a heritable basis for coloration as well as a phenotypic response based on environment. It is thought that background color is based on environment (Westley and others, 2013), while spotting characteristics have a heritable basis (Blanc and others, 1982; 1994; Skaala and Jørstad, 1988; Skaala and others, 1992). It has been shown that one can discriminate between native and hatchery brown trout as well as hybrids based on the number and shape of parr marks (Blanc and others, 1982; Mezzera and others, 1997). One can also discriminate different strains of brown trout based on coloration and spotting patterns (Aparico and others, 2005). Thus it might be possible to determine if brown trout within the Colorado River system are one panmictic population or comprised of various metapopulations based on differing phenotypic characteristics.

We propose to quantify the colorations and spotting patterns of brown trout at various locations within the Colorado River and tributaries between Glen Canyon Dam and Lake Mead. Digital images of fish will be taken with a Munsell color chart and a scale. The shape, color, size, number, and location of spots (and parr marks for juvenile fish) will be quantified using a digital imaging program (e.g., ImageJ, tpsDIG2).

This project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.6. Mainstem translocation of humpback chub

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
D. Van Haverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
David Ward, Fishery Biologist, USGS, GCMRC
William Persons, Fishery Biologist, USGS/GCMRC

A long standing goal of managers has been establishing a second spawning population of humpback chub in Grand Canyon. The USFWS issued a Biological Opinion (U.S. Fish and Wildlife Service, 1995) concerning the preferred Modified Low Fluctuating Flow alternative on the Operation of Glen Canyon Dam EIS (U.S. Department of the Interior, 1995), whereby one element of the reasonable and prudent alternative (RPA) was to “Make every effort to establish a second spawning aggregation of humpback chub downstream of Glen Canyon Dam.” To address this RPA, Valdez and others, (2000) produced a research and implementation plan for establishing a second spawning population of humpback chub in Grand Canyon. The conclusions in Valdez and others, (2000) were: 1) the highest chance for success of establishing a viable mainstem spawning population for humpback chub would be in the mainstem itself, and 2) experimental translocations into side tributaries should be conducted. The second recommendation of Valdez and others (2000) has been implemented with promising success at Shinumo and Havasu Creeks. This project would attempt to more directly address the first recommendation of Valdez and others, (2000).

Humpback chub have been successfully translocated into Shinumo and Havasu Creeks, and emigrants from these tributaries have augmented their respective mainstem aggregations (Persons and others, *in prep*). These translocations are thought to have been successful in augmenting mainstem aggregations in part because the tributaries provide suitable rearing habitat for juveniles before some emigrate into the mainstem. Many translocated humpback chub that have emigrated from Shinumo and Havasu Creeks and were subsequently captured in the mainstem have been sub adults (<200 mm), suggesting that direct augmentation of small humpback chub into the mainstem may be feasible. This approach could be an avenue to augment aggregations or other groups of humpback chub not located near tributaries. Approximately 250 juvenile (<100 mm) or larval humpback chub will be collected annually from the LCR as part of Project Element 7.1. Fish will be transported out of the LCR by helicopter and then transported to Southwestern Native Aquatic Resources and Recovery Center (SNARRC) along with humpback chub designated for Shinumo and Havasu Creeks. Once at SNARRC, fish will undergo quarantine procedures and will be reared for a year until reaching ~150 mm TL. Fish will be PIT tagged, and transported back to Grand Canyon. They will then be transported either by boat or by helicopter to a release site. The eventual release site will be decided upon by management agencies, with input from cooperators. One possible location would be within, or adjacent to, the Pumpkin Spring aggregation. This area may be favorable for humpback chub rearing due to the presence of springs, several large eddy complexes, at least one large backwater, a large cove, several gravel producing debris fan inflows, and relatively warm water.

Fish will be tempered and soft released in large eddy complexes, backwaters or slow current areas. Release of fish would likely occur in September or possibly earlier if it is possible to grow chub to a sufficient size at SNAARC. Annual monitoring would occur during mainstem aggregation trips. Additional monitoring could be possible if release occurs near the Pumpkin Spring aggregation, and upriver access was granted from Diamond Creek. The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.7 Rainbow Trout Early Life Stage Survey

Luke Avery, Fishery Biologist, USGS, GCMRC
G. Dave Foster, Logistic Support, USGS, GCMRC

The objective of the RTELSS study is to monitor the response of the age-0 population of rainbow trout in Lees Ferry to variations in Glen Canyon Dam operations and to naturally occurring disturbances to the CRe in Glen Canyon.

Understanding of the effects of various physical and biological conditions on the age-0 rainbow trout population will enable better management practices to attain desired rainbow trout abundance and population structure. Monitoring of the age-0 population also provides early indication of potential changes to the juvenile and adult rainbow trout population, providing the potential for early response to undesirable conditions. This monitoring will answer the following questions: 1) how do changes in the conditions (e.g., bed texture, flow, aquatic vegetation, and sediment supply) of the Colorado River in Glen Canyon effect the age-0 population of rainbow trout? 2) How can dam operations be experimentally evaluated to determine whether or not they might be used to manage the rainbow trout population via influences on the young-of-the-year population?

The RTELSS program was initiated in January 2003 to monitor the effects of the nonnative fish suppression flows (NFSF) that occurred during January through March from 2003–2005 (Korman and others, 2005). Since then it has provided information on the response of the age-0 rainbow trout population to higher flow dam releases that have occurred in March through June 2008, and falls of 2011, 2012, and 2013, as well as the response to the equalization flows that occurred in spring through fall 2011. An understanding of the response of the age-0 rainbow trout population to these flow events has provided a more mechanistic understanding of correlated changes that have occurred in the adult rainbow trout population and downstream emigration events that have been associated with some of those changes (Korman and others, 2012, Makinster and others, 2011, Melis and others, 2012). Maintaining the RTELSS as a monitoring program ensures sufficient data will be available to detect a response of the age-0 rainbow trout population to changes in the CRe within Glen Canyon, whether those changes in the system be by scientific design or not. Understanding of the response of age-0 rainbow trout to various conditions and events may enable management to better maintain the balance between a blue ribbon rainbow trout fishery and the welfare of the endangered native humpback chub.

The RTELSS program monitors egg deposition in winter and early spring and proceeds with monitoring of population dynamics through summer, fall, and early winter. Monitoring of egg deposition consists of 9-10 redd surveys conducted from December through May. Data collected provides information on the timing and magnitude of the spawn that provides the foundation for the year's cohort of fish. Larval and juvenile fish sampling (backpack and boat electrofishing) trips occur once a month in June-September and November. Data collected provides information on hatch success and early survival, as well as survival through the year. Otoliths extracted from specimens collected across trips provide information on growth and hatch distribution. Survey, sampling, and data analysis details can be found in in Korman and others (2009), and Korman and others (2011).

Project Element 6.8. Lees Ferry Creel Survey

David Rogowski, Fishery Biologist, AGFD
William Persons, Fishery Biologist, USGS, GCMRC

The objective of this project element is to evaluate how changes in the conditions of the Colorado River in Glen Canyon affect angler effort, catch and harvest on an annual basis

The blue ribbon rainbow trout fishery of Lees Ferry has been identified as a key resource of the Colorado River in Glen Canyon under the purview of the Glen Canyon Dam Adaptive Management Program (GCDAMP) and so must be maintained. The Lees Ferry trout fishery is located in the tailwater portion of the Colorado River ecosystem from Glen Canyon Dam to the Paria River. The status and trends of the fishery are regulated by biotic and abiotic mechanisms that may in turn be affected by the operations of Glen Canyon Dam.

Creel surveys are an effective tool to monitor a variety of metrics such as: the impact of recreational fishing on the fishery (harvest rates), angler use (indirect measure of economic impact), and angler satisfaction (Malvestuto 1996). Creel surveys are also an effective way to maintain an active presence with the fishing public, provide needed outreach, as well as feedback and observations about the fishery from the public. Anglers are often the first to notice changes in fish health or invasive species. Angler creel surveys will be conducted to estimate angler effort, catch and harvest. Monitoring basic angler statistics including angler usage (anglers/year), catch-per-unit-effort, and harvest rates provide information necessary to assess the status of these resources and inform the Adaptive Management Program. GCDAMP funded the Arizona Game and Fish Department to collect creel survey data in FY13 and 2014. AGFD agreed to fund the surveys during FY15 and GCDAMP will fund this effort during FY16 and FY17.

D.2 Personnel and Collaborations

The overall lead for Project 6 is William Persons a fishery biologist with GCMRC. Kirk Young and David Van Haverbeke are fishery biologists with the U.S. Fish and Wildlife Service with extensive humpback chub experience and will lead the humpback chub aggregation project (6.1). Brian Healy is a fishery biologist with Grand Canyon National Park with expertise in humpback chub translocations and humpback chub aggregations at Shinumo and Havasu Creeks. Mr. Healy will assist with humpback chub aggregation studies (6.1 and 6.2), the PIT tag antenna project (6.3) and mainstem translocation of humpback chub (6.6). Dr. Karin Limburg is a professor at State University of New York who specializes in otolith microchemistry and will be the lead for the humpback chub recruitment project (6.2). Michael Dodrill is a fishery biologist with GCMRC with extensive experience sampling for young-of-the-year humpback chub and will assist with the humpback chub recruitment project (6.2). David Ward is a fishery biologist with GCMRC that maintains and operates the GCMRC experimental laboratory facility at Northern Arizona University. He will provide expertise in sampling young-of-the-year humpback chub (6.2) the PIT tag antenna project (6.3) and the translocation of humpback chub (6.6). Dr. David Rogowski is a fisheries biologist with Arizona Game and Fish Department with expertise in aquatic ecology and conservation biology of fish, and will lead the System Wide Electrofishing project (6.4), the brown trout natal origins project (6.5) and the Lees Ferry Creel Survey project (6.8). Dr. Michael Collyer is an Assistant Professor at Western Kentucky University with expertise in development of quantitative methods for analyzing phenotypic change and will provide technical support for the brown trout natal origins project. Luke Avery is a GCMRC fishery biologist with GCMRC and is the lead for the RTELSS (6.7). Dave Foster is a GCMRC River Operations Mechanic and Lees Ferry fishing guide and will assist with the RTELSS project. Thomas Gushue is a GCMRC GIS specialist, expert in collecting, processing and analyzing spatial data in Grand Canyon.

D.3 Deliverables

Project elements will produce annual progress reports and peer reviewed publications at project completions.

E. Productivity from Past Work (during FY 13–14)

During FY13 the following products were delivered to GCMRC prior to April 1, 2014.

E.1. Data Products

Data, trip reports and annual reports:

Trip ID	Project
GC20130404	System Wide Electrofishing and catfish angling, Lees Ferry to Diamond Creek
GC20130525	System Wide Electrofishing and catfish angling, Lees Ferry to Diamond Creek
GC20131028	System Wide Electrofishing and catfish angling, Diamond Creek to Lake Mead Rogowski, D.L. and P.N. Wolters. Colorado River Fish Monitoring in Grand Canyon, Arizona – 2013 Annual Report.
GC20130720	Mainstem netting, July aggregation monitoring
GC20130907	Draft manuscript in preparation: Persons, W.R. and D.R. Van Haverbeke. Colorado River Fish Monitoring in Grand Canyon, Arizona: 2002—2013 Humpback Chub Aggregations.
RTELSS	RTELLS survey results. Draft manuscript submitted. Avery, L.A. and others, 2014, Effects of increased discharge and temperature on age-0 rainbow trout dynamics in Lees Ferry, AZ

Linder, C.M., R.A. Cole, T.L. Hoffnagle, B. Persons, and A. Choudhury. 2012. Parasites of fishes in the Colorado River and selected tributaries in Grand Canyon, Arizona. Journal of Parasitology 98(1) pp 117-127.

Makinster, A.S., Persons, W.R., and Avery, L.A., 2011, Status and trends of the rainbow trout population in the Lees Ferry Reach of the Colorado River downstream from Glen Canyon Dam, Arizona, 1991–2009: U.S. Geological Survey Scientific Investigations Report 2011-5015, 17 p., http://pubs.usgs.gov/sir/2011/5015/.

Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona--2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010-1246, 26 p., http://pubs.usgs.gov/of/2010/1246/.

E.2. Publications in progress

Persons, W.R. and D.R. Van Haverbeke. 2014. Colorado River Fish Monitoring in Grand Canyon, Arizona: 2002—2013 Humpback Chub Aggregations.

Avery, L.A. 2014. Effects of increased discharge and temperature on age-0 rainbow trout dynamics in Lees Ferry, AZ.

Bunch, A.J., W.R. Persons, and W.T. Stewart. 2014. Integrating stationary PIT antennas into evaluations of fish sampling gear. *In review*.

Pearson, K.N., W.L. Kendall, D.L. Winkelman, and W.R. Persons. 2014. Evidence for skipped spawning in the endangered humpback chub (*Gila cypha*) with implications for demographic parameter estimates. *In review*.

E.3. Presentations at GCDAMP meetings

Healy, B., E.Omana Smith, C. Nelson, M. Trammel, M. McKinstry, B. Albrecht, and R. Kegerries. Native Fish Population Trends – Grand Canyon Tributaries and Razorback Sucker: Status and Habitat Use. January 28, 2014 , Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ.

Persons, W.R., D.R. Van Haverbeke and B. Healy. Colorado River fish monitoring in Grand Canyon, Arizona: 1990-2013 humpback chub, Gila cypha, aggregations. January 28, 2014 Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ.

Rogowski, D. and B. Healy. Other native fishes: population status and trends in the Colorado River and tributaries. January 28, 2014, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ.

Rogowski, D. Colorado River trout population monitoring: spawning and rearing surveys, seasonal and annual electrofishing surveys, and creel survey. January 28, 2014, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ.

Young, K. and B. Healy. Humpback chub in the Little Colorado River and other tributaries: monitoring of juveniles, sub-adults, and adults and translocations. January 28, 2014, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ.

E.4. Presentations at professional meetings

Persons, W.R., D.R. Van Haverbeke and B. Healy. Colorado River fish monitoring in Grand Canyon, Arizona: 1990-2012 humpback chub, Gila cypha, aggregations. Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

Rogowski, David. Does variation in sampling effort during a long term monitoring project matter? Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

Brizendine, M.E., D.L. Ward and S.A. Bonar. Use of ultrasonic imaging and Ovaprim® to evaluate egg maturation of humpback chub, Gila cypha. Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

Omana Smith, E., B. Healy, C. Nelson and M. Trammell. Endangered humpback chub translocations to Colorado River tributaries in Grand Canyon National Park. Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

Healy, B., C. Nelson, E. Omana Smith, and M. Trammell. Non-native fish control in Colorado River tributaries in Grand Canyon National Park . Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

Van Haverbeke, D.R., M.J. Pillow, D.M. Stone and K.L. Young. Monitoring of humpback chub, bluehead sucker, and flannelmouth sucker in the Little Colorado River, Grand Canyon, Arizona. Desert Fishes Council Annual Meeting, November 20-24, 2013, Flagstaff, AZ.

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Table 1. Administrative History of Project 6.

Project	FY11-12	FY13-14	FY15-17
Mainstem Fish Studies			
6.1. Humpback chub aggregation monitoring.	FY11: BIO 2.M4.11 $283,090 FY12: BIO 2.M4.12 $539,107	FY13: D.1 $203,900 FY14: D.1 $210,000	FY15: $218,768 FY16: $249,888 FY17: $252,6332
6.2 Humpback chub aggregation recruitment.		FY13: D.2 $167,400 FY14: D.2 $155,300	FY15: $83,750 FY16: $53,680 FY17: $50,048
6.3 Detecting aggregations with PIT tag antennas (new project)			FY15: $18,444 FY16: $13,500 FY17: $ 9,216
6.4 System Wide Electrofishing (SWEF)	FY11: BIO 2.M4.11 $283,090 FY12: BIO 2.M4.12 $539,107	FY13: F.1 $220,500 FY14: F.1 $227,200	FY15: $283,722 FY16: $295,900 FY17: $298,522
6.5 Brown trout origins through body pigmentation patterns. (new project)			FY15: $16,146
6.6 Humpback chub translocation to mainstem locations. (new project)			FY15: $ 9,790 FY16: $10,152 FY17: $10,782
6.7 Rainbow trout early life stage survey (RTELSS)	FY11 BIO4.M2.11 No line item for this project	FY13-14: F2.2 No line item for this project	FY15: $77,024 FY16: $69,296 FY17: $74,112
6.8 Lees Ferry Creel Survey	FY11 BIO4.M2.11 No line item for this project	FY13-14: F2.3 No line item for this project	FY15: FY16: $25,750 FY17: $25,750
Related Projects			
7.2 Juvenile Chub Monitoring near LCR confluence (NSE and JCM). Integrated with **6.4**	NSE BIO 2.R15.11 $697,039 NSE BIO 2.R15.12 $423,475	FY13: F.3 $474,600 FY14: F.3 $488,800	FY15: $492,700 FY16: $510,900 FY17: $182,600
9.2 Rainbow trout movement (Natal Origins). Integrated with **6.4**	BIO 2.E.18.11 $432,518 BIO 2.E.18.12 $453.029	FY13: F.6 $281,800 FY14: F.6 $290,300	FY15: $440,500 FY16: $484,900 FY16: $371,900

G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
X							6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$187,000**	**$4,900**	**$29,700**	**$100,300**	**$305,000**	**$0**	**$59,500**	**$686,400**
				X			6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$55,400	$1,000	$6,100	$36,700	$100,000	$0	$18,500	$217,700
		X					6.2	Aggregation recruitment	Dodrill et al.	$35,400	$0	$6,400	$8,800	$25,000	$0	$8,700	$84,300
X							6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$8,100	$0	$7,800	$0	$0	$0	$2,500	$18,400
		X					6.4	System Wide Electrofishing	Persons and Rogowski	$31,900	$0	$8,100	$49,200	$165,000	$0	$18,900	$273,100
		X		X			6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$600	$0	$15,000	$0	$500	$16,100
X	X						6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0
X	X						6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$56,200	$3,900	$700	$5,600	$0	$0	$10,400	$76,800
X							6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$0	$0	$0	$0

Monitoring		Research															
Core activities	**Support implementation and evaluation of HFE Protocol and Non-Native Fish Control**	**Technical and analytical innovations in monitoring**	**Improving predictive modeling capacity**	**Resolving scientific uncertainty**	**Independent science oversight and review**	**Integrating tribes in monitoring and research**	**Project Identifier**	**Project Description**		**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Coop-erators (non-USGS)**	**USGS Coop-erators**	**USGS/SBSC Burden**	**Total**
FY16																	
X							**6**	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$180,100**	**$5,700**	**$21,200**	**$118,000**	**$305,000**	**$0**	**$78,600**	**$708,600**
				X			6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$62,500	$1,200	$6,200	$44,300	$100,000	$0	$27,400	$241,600
		X					6.2	Aggregation recruitment	Dodrill et al.	$31,000	$500	$3,500	$9,000	$0	$0	$9,400	$53,400
X							6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$8,400	$0	$2,700	$0	$0	$0	$2,400	$13,500
		X					6.4	System Wide Electrofishing	Persons and Rogowski	$22,700	$0	$8,100	$59,700	$165,000	$0	$24,200	$279,700
		X		**X**			6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$0	$0	$15,000	$0	$500	$15,500
X	**X**						6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0
X	**X**						6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$55,500	$4,000	$700	$5,000	$0	$0	$13,900	$79,100
X							6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$25,000	$0	$800	$25,800

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
X							**6**	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$189,800**	**$5,700**	**$26,300**	**$118,300**	**$340,000**	**$0**	**$103,500**	**$783,600**
				X			6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$63,300	$1,200	$6,200	$44,200	$100,000	$0	$34,500	$249,400
		X					6.2	Aggregation recruitment	Dodrill et al.	$26,000	$500	$3,500	$9,100	$0	$0	$10,700	$49,800
X							6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$4,400	$0	$2,800	$0	$0	$0	$2,000	$9,200
		X					6.4	System Wide Electrofishing	Persons and Rogowski	$30,700	$0	$8,100	$60,000	$185,000	$0	$32,600	$316,400
		X		X			6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$0	$0	$0	$0	$0	$0
X	X						6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$4,400	$0	$5,000	$0	$30,000	$0	$3,500	$42,900
X	X						6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$61,000	$4,000	$700	$5,000	$0	$0	$19,400	$90,100
X							6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$25,000	$0	$800	$25,800

Project 7. Population Ecology of Humpback Chub in and around the Little Colorado River

Initial Estimate: FY15: $1,290,100; FY16: $1,493,200; FY17: $1,364,600

GCDAMP Funding: FY15: $1,290,100; FY16: $1,388,700; FY17: $1,296,400

Other BoR Funding: FY15: $261,000; FY16: $215,400; FY17: $0

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B. Project Summary

During 2013–14 we developed models that integrate data collected in the Little Colorado River (LCR) with data collected by the juvenile chub monitoring (JCM) project to provide a holistic picture of humpback chub (*Gila cypha)* population dynamics (Yackulic and others, 2014). This manuscript suggests that chub movement between the LCR and Colorado River prior to adulthood is relatively rare, with the exception of young-of-the-year outmigration and that growth and survival rates are very different in these two environments. This journal article also identified the need for studies of trap avoidance among older humpback chub in the LCR, a need that can potentially be addressed by increased use of remote technologies for detecting humpback chub. We then used a modified version of these models to explain interannual variability in mainstem growth and survival in terms of monthly temperature and estimated rainbow trout (*Oncorhynchus mykiss*) abundances in order to support the development of the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement and address the key uncertainty surrounding the relative importance of rainbow trout and temperature in humpback chub population dynamics (Yackulic and others, in prep.). While parameter estimates in these models are based on field data collected in the LCR and JCM, this modelling was aided conceptually by lab experiments exploring impacts of trout and temperature on chub growth and survival (Ward and others, in prep).

Simulating future dynamics under alternative management strategies as part of the LTEMP process highlighted the importance of uncertainty associated with several key population processes, especially the production and outmigration of young-of-the-year humpback chub from the LCR. Available information suggests that the number of Age-0 chub present in July in the LCR has varied from roughly 5,000 to 50,000 in recent years and that the overall outmigration rate can vary from 25% to 75%. To address this uncertainty, already identified in the Grand Canyon Monitoring and Research Center's workplan for Fiscal Years (FY) 2013–14, we initiated juvenile humpback chub marking with visible implant elastomer (VIE) tags in the LCR during early July, a period when humpback chub are just becoming large enough to have a reasonable chance of surviving in the mainstem. Although LTEMP obligations have delayed a formal analysis of these data, preliminary work suggests that this effort will allow us to estimate juvenile humpback chub abundance and outmigration with acceptable precision. We also analyzed data collected by the U.S. Fish and Wildlife Service (USFWS) from 2001–2013 to characterize spatio-temporal variation in survival, growth and movement of sub-adult humpback chub in the LCR (Dzul and others, in review). This work suggests both that winter growth is strongly and negatively correlated with the extent of winter/spring flooding and that habitat quality for sub-adult humpback chub is better in upper reaches of the LCR. This follows work by Vanhaverbeke *and others* (2013) indicating that when winter/spring flooding was minimal, juvenile production was poor. Other activities during FY13–14 included pilot work to determine the best ways to characterize spatio-temporal variation in the food base in FY13, with plans to rigorously sample the LCR food base in calendar year 2014.

In FY15–17, we will: (a) continue to monitor humpback chub in the LCR and Colorado River reference site (river mile (RM) 63.0-64.5) and to mark young-of-year humpback chub throughout the lower 13.6 km of the LCR in July, (b) develop field and analytical techniques to better use remote technologies for detecting passive integrated transponder (PIT) tags to address questions of trap avoidance and to potentially minimize future handling of chub, (c) develop new non-lethal tools for measuring the health and condition of humpback chub in the field, (d) undertake targeted, cost-effective research to understand mechanisms underlying observed population processes, including the roles of high CO_2 at base flow, gravel limitation, parasites, and the aquatic food base, and (e) continue to develop models that integrate findings from the above projects. The proximate goals of these activities is to better understand the relative roles of LCR hydrology, water quality, intraspecific and interspecific interactions, and mainstem conditions in humpback chub juvenile life history and adult recruitment, as well as to better estimate the current adult abundance. The ultimate goal of these activities is to continue to develop tools that allow us to better predict the impacts of dam operations and other management activities on humpback chub populations as well as appropriately account for uncertainty in these predictions. Specific questions of interest include:

1. To what extent does young-of-the-year humpback chub production and outmigration from the LCR vary between years and how is this variation driven by LCR hydrology and intraspecific interactions (i.e., cannibalism and competition)?
2. What are the drivers of interannual and spatial variation in survival and growth of juvenile and sub-adult humpback chub? In particular, what are the roles of LCR and mainstem conditions in the overall trajectory of the population?
3. Are there factors, such as heterogeneity in skip-spawning rates, heterogeneity in adult humpback chub capture probabilities in the JCM, or trap avoidance in the LCR that bias estimates of the adult population size and population processes?

Juvenile humpback chub are the most sensitive life stage to mainstem conditions and an understanding of their life history is the key to predicting the influence of dam operations on this species. Prior to the Near Shore Ecology (NSE) project (2009–2011) and the more recent JCM project (2012–current), our understanding of humpback chub early life history was limited to back-calculations of cohort strength (number of fish surviving to adulthood from a given hatch year) derived from abundance estimates of humpback chub greater than 200 mm and believed to be four years old (Coggins and others, 2006; Coggins and Walters, 2009). However, given the disparity in growth rates between humpback chub living in the LCR and Colorado River (Yackulic and others, 2014) this approach was almost certainly misleading as humpback chub could be anywhere from 4–10 years old when they reach 200 mm depending on where they had spent most of their time (LCR or mainstem Colorado River) and what environmental conditions had been like in those locations.

Since 2009, we have developed the field techniques (including a fixed reference site in the Colorado River) and analytical methods that allow us to understand humpback chub early life history in the detail required to begin to tease apart the effects of variation in population processes caused by mainstem temperature, trout abundance, and conditions in the LCR. For example, in support of the LTEMP process we were able to fit relationships between monthly temperature and estimated rainbow trout abundance and juvenile humpback chub survival and growth using only data from 2009–2013 that accurately predicted trends in adult humpback chub numbers from 1989–2009 (Figure 1). While there is still room for improvement in these models,

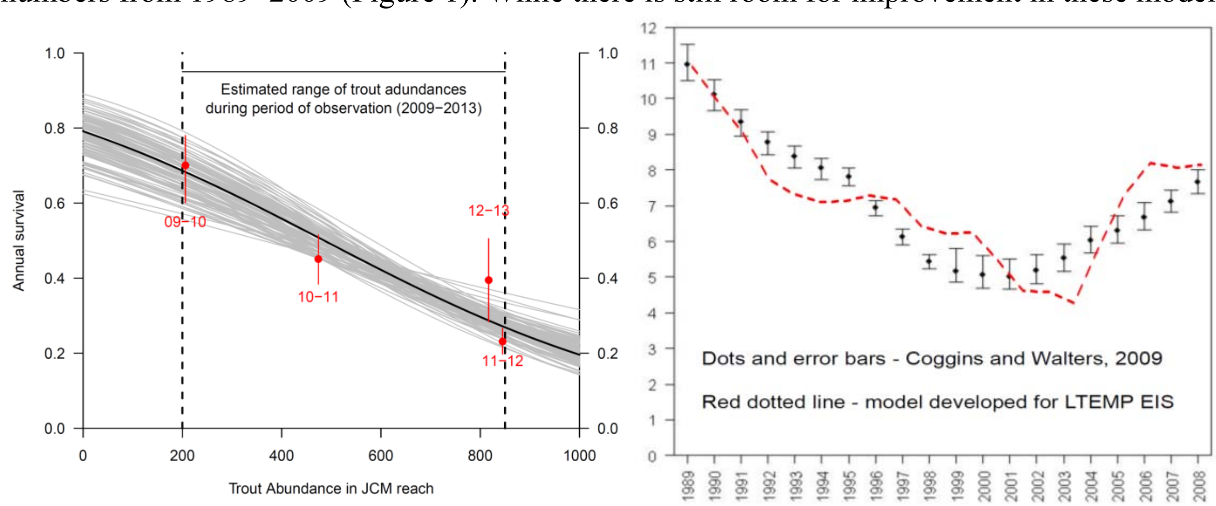

Figure 1: (left) Annual survival of juvenile humpback chub in the mainstem Colorado estimated annually (July to July) in red versus estimates using estimated trout abundance as a covariate. (right) Backcasting using temperature and trout relationships estimated from 2009-2013 data, as well as trout estimates and measured temperatures match well with estimates from previous population assessments. (Preliminary data, do not cite).

this represents a dramatic step in our ability to predict the consequences of management options. While conditions in the LCR are not directly affected by dam operations, they nonetheless play a vital role in determining the degree to which temperature and rainbow trout numbers in the Colorado River must be managed (Figure 2). For example, if juvenile humpback chub production and export are high, this may suggest less need for rainbow trout management and/or lower flows to increase water temperatures in the mainstem. Alternatively, a better understanding of the factors leading to increased humpback chub production could provide decision makers opportunities to strategically implement management actions in years when they would have the largest effect. For example, the 2000 Low Steady Summer Flow experiment may have been ineffective simply because it followed two years of potentially minimal production of juvenile chub. Improved information about the drivers of humpback chub population dynamics could have helped managers and scientists plan this experiment such that it occurred when conditions were more likely to result in a detectable response. Likewise, management actions such as mechanical removal of nonnative fishes will be much more effective if they occur in years of high humpback chub production. If variation in production is primarily driven by exogenous factors (e.g., extent of flooding) as opposed to endogeneous factors (e.g., competition between cohorts) this also has implications for long-term population dynamics.

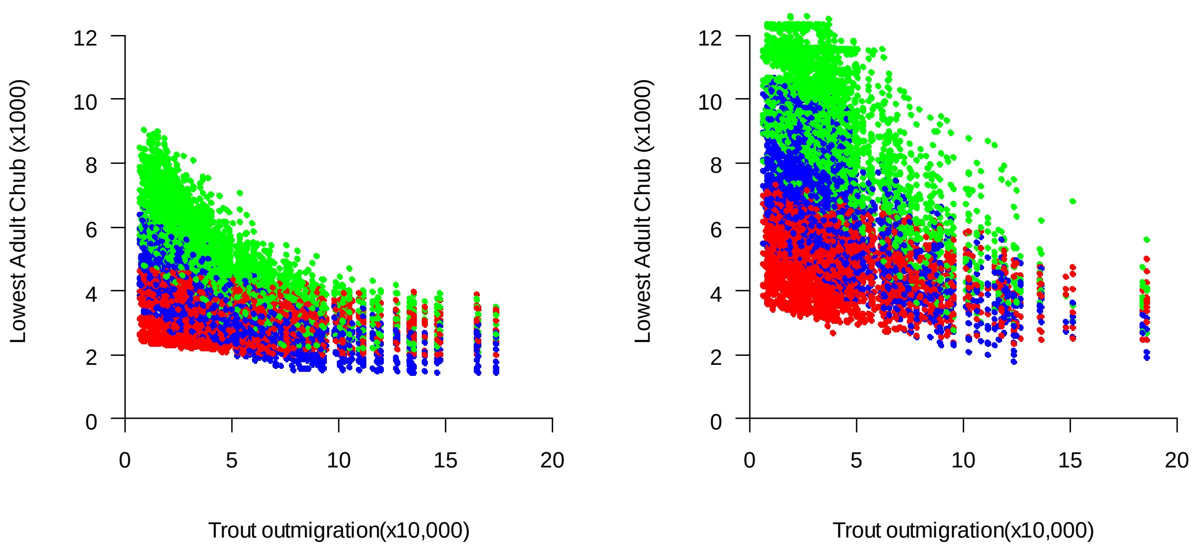

Figure 2: Predicted minimum adult humpback chub population sizes over twenty year simulations (each dot represents a simulation based on different alternatives and/or potential parameter values). Different plots are for wetter/warmer (left) and drier/colder (right) hydrologic traces. Colors represent high (green), medium (blue), and low (red) humpback chub recruitment scenarios. (Preliminary data, do not cite)

With respect to adult humpback chub, key uncertainties revolve around our understanding of capture probability and movement. In particular, heterogeneity in capture probability in the LCR caused by some adult humpback chub (especially potential residents) avoiding hoop nets could lead to underestimates of abundance. At the same time, the potential for temporary emigration in the JCM reach is a cause for concern and could lead to overestimates of abundance. Lastly, a better understanding of skip-spawning in adult humpback chub is essential because many adults are only vulnerable to capture during spring sampling in the LCR and thus inferences about their survival and abundance depends on assumptions about the skip-spawning process. Answering the above uncertainties is dependent both on new data streams from remote tag readers and intellectual investment into developing the appropriate models to incorporate this information and test hypotheses.

C. Background

C.1. Scientific Background

Standardized sampling in the LCR over the last decade has revealed substantial year to year variation in relative abundances of juvenile humpback chub in the fall (VanHaverbeke and others, 2013). In particular, juvenile catch in 2002 and 2006 was markedly lower than other years and occurred in the same years as relatively low winter/spring discharge in the LCR over the same span, suggesting an important and unresolved link between LCR hydrology and humpback chub population dynamics. On the other hand, there appears to be substantial variation in fall juvenile relative abundances in others years (e.g., 2009 and 2013 were relatively low) that appears to be unrelated to winter/spring discharge.

There are at least four hypotheses to explain this linkage, each of which has different implications for the significance of the observation—low juvenile fall abundance in the LCR—to humpback chub population dynamics and adult recruitment. These hypotheses also have different implications for the relative roles of conditions in the mainstem Colorado versus the LCR in determining adult humpback chub population dynamics and adult recruitment. Low juvenile abundance in the fall could be a leading indicator of a failed hatch year caused by: (Hypothesis-(**H1**) poor egg survival in the LCR associated with gravel limitation (**H1a**) or high CO2 levels (**H1b**), (**H2**) poor juvenile survival in the LCR the preceding summer associated with low prey production, (**H3**) low juvenile survival in the LCR the preceding summer due to predation by conspecifics, or (**H4**) unrelated to juvenile survival and instead a result of outmigration from the LCR due to displacement from monsoon floods or relatively favorable rearing conditions in the mainstem Colorado River.

Under Hypothesis 1 (**H1**) Survival of humpback chub eggs in the LCR is limited in years when snowmelt flooding is negligible or small because of poor spawning substrate conditions or high CO2 conditions that limit egg and larval survival. The rationale for this spawning limitation hypothesis is that the LCR is a high CO2, travertine system, and marl deposition in the lower LCR is extremely rapid (Robinson and others, 1996). Without moderate/large snowmelt floods that deliver lower CO2 water and clean gravels, substrates in the downstream part of the LCR during the spawning season will likely be cemented together with marl and will lack the interstitial spaces and/or water quality necessary for egg survival. Under this hypothesis, we would expect lowered numbers of juveniles in both the LCR and in the mainstem near the LCR confluence during years without large LCR snowmelt floods. Further, if this hypothesis is true, it suggests that the continued success of the LCR population may be predicated on climatic conditions in the LCR basin and are best in years of moderate/large snowmelt floods. H1b may also explain the lower frequency of juvenile chub in upper portions of the LCR, where CO2 concentrations are greater.

Under Hypothesis 2 **(H2)** Large snowmelt floods in the LCR stimulate production of the prey base through improvements in both the quantity and quality of food resources consumed by humpback chub, which leads to high juvenile humpback chub survival and low outmigration. (**H2)** is somewhat related to **H1** in that it also posits a link between LCR hydrology and juvenile abundance in the fall, but the mechanism underlying **H2** is different. In years with small snowmelt floods, the foodbase in the LCR is unproductive (see Fisher and others, 1982; Cross and others, 2011), which in turn leads to low survival and/or high out-migration of juvenile humpback chub. Under this hypothesis, the population of juvenile humpback chub (both yearlings and young-of-year) in the mainstem could remain the same, or even increase, if juveniles choose to outmigrate in response to low food densities in the LCR in years without substantial snowmelt flooding. If this hypothesis is true, and there is earlier and higher outmigration in response to negligible/small snowmelt floods in the LCR, it suggests that mainstem conditions may be especially important as a greater proportion of the juvenile population will be rearing in the mainstem.

Hypothesis 3 **(H3)** focuses on the role of intraspecific interactions, especially predation and cannibalism by yearlings on young-of-the-year, and can take two non-mutually exclusive forms. The first variety of this hypothesis (**H3a)** posits that in years without large LCR snowmelt floods, more yearlings remain in the system and there are higher levels of cannibalism and competition than in years with large LCR snowmelt floods. The second version **(H3b)** posits that, independent of the reason for decreases in fall abundances in 2002 and 2006, the lack of yearlings in the LCR in the following spawning season (2003 and 2007) led to especially large cohorts of young-of-year in those hatch years because of reduced cannibalism and competition. It is also possible that snowmelt floods are not an important factor affecting humpback chub dynamics and, instead, the intensity of summer/fall monsoon floods is the primary driver of fall abundances of juvenile humpback chub; that is, low LCR fall abundances are not a leading indicator of a failed hatch year. In both 2002 and 2006, LCR discharge during the snowmelt season was negligible, but there were relatively large monsoon floods in the fall. This observation leads to Hypothesis 4 **(H4),** which argues that outmigration rates of juvenile humpback chub from the LCR are directly linked to the intensity of monsoon flooding in the summer and fall. Under this hypothesis, we would expect increased migration from the LCR to the mainstem during years of large monsoon flooding in the LCR, and we would expect most migration to occur during the monsoon season—from July to September. VIE marking as part of both USFWS and NSE sampling between 2009 and 2011 has provided hints of movement between the LCR and the mainstem over these time scales; however, interpretation of these data has been hampered by the relatively low number of juveniles marked between the spawning season and before fall monsoons. Specifically, the last scheduled spring marking event in the LCR occurs in May, and young-of -year humpback chub are rarely large enough to mark with VIE tags (>40 mm total length). The next scheduled marking occurs in September, and monsoon floods that displace young-of- year may have already occurred.

Survival rates for juvenile fish are highly correlated with individual growth rates; a juvenile population that grows rapidly will generally experience higher survival relative to a population of juveniles that is growing slowly (Walters and Martell, 2004). Understanding the causes of variation in juvenile humpback chub growth rates among habitats will therefore aid interpretation of any estimates of juvenile survival among habitats. One hypothesis to explain the observed variation in humpback chub growth rates among locations and times is that growth rates are mainly driven by concomitant changes in water temperature **(H5)**. This hypothesis has clear implications for dam operations. Another hypothesis **(H6)** states that humpback chub growth among locations and times is mainly driven by differences in the quantity and quality of prey available to juvenile humpback chub. This hypothesis also has implications for dam operations, but the types of operational changes that might be evaluated to mitigate low prey production in the mainstem are very different from the types of operations that might be evaluated to mitigate water temperature effects related to (**H5)**. Lastly, interspecific and intraspecific competition for food resources is the main driver of humpback chub growth rates among locations and times **(H7)**. These hypotheses (**H5-H7**) are obviously not mutually exclusive. **H6** and **H7**, in particular, are linked because food limitation (**H6**) is a necessary condition for resource competition (**H7**). We believe the distinction is important, however, because LCR hydrology may have strong effects on resource availability (**H6**) independent of fish abundance (**H7**). Thus, there may be some years when one factor ultimately limits or constrains humpback chub growth, and other years when a different factor limits growth.

It is improbable that a two-year study could fully resolve all of these hypotheses, in part because our ability to distinguish among certain hypotheses is dependent on LCR hydrology. However, irrespective of LCR hydrology, the activities we will conduct in FY15–17 will allow us to evaluate the strength of evidence for at least some of the above hypotheses and address key uncertainties surrounding the population dynamics of humpback chub. This new research will be integrated with ongoing USFWS monitoring in the LCR and JCM sampling in the mainstem, which will help minimize handling of juvenile humpback chub. Integration of this new research effort into ongoing monitoring will also build upon these long-term efforts in a way that allows us to ask new questions.

C.2. Management Background

This project directly addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) previously identified by the Glen Canyon Dam Adaptive Management Program (GCDAMP).

- **Goal 2:** Maintain or attain a viable population of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats.
- **Goal 4:** Maintain a naturally reproducing population of rainbow trout above the Paria River, to the extent practicable and consistent with the maintenance of viable populations of native fish.

In August 2004, the GCDAMP Adaptive Management Work Group reviewed these goals and identified priority questions. This project addresses the top priority question:

- **Priority 1**: Why are humpback chub not thriving, and what can we do about it? How many humpback chub are there and how are they doing?

In March 2011, the Secretary's Designee, Assistant Secretary for Water and Science, identified that the first priority was compliance with the Endangered Species Act, followed by sediment, with the third priority being science on both non-native control and the recreational trout fishery. These monitoring projects contribute to improved understanding of humpback chub, rainbow trout, and their interactions.

C.3. Key Monitoring and Research Questions Addressed in this project

Primary SSQ addressed:

- **SSQ 1-1.** To what extent are adult populations of native fish controlled by production of young fish from tributaries, spawning and incubation in the mainstem, survival of young-of-year and juvenile stages in the mainstem, or by changes in growth and maturation in the adult population as influenced by mainstem conditions?
- **SSQ 1-2.** Does a decrease in the abundance of rainbow trout and other cold- and warm water nonnatives in Marble and eastern Grand Canyons result in an improvement in the recruitment rate of juvenile humpback chub to the adult population?

Additional SSQs addressed:

- **SSQ 1-8.** How can native and nonnative fishes best be monitored while minimizing impacts from capture and handling or sampling?
- **SSQ 5-4.** What is the relative importance of increased water temperature, shoreline stability, and food availability on the survival and growth of YoY and juvenile native fish?
- **SSQ 5-6.** Do the potential benefits of improved rearing habitat (warmer, more stable, more backwater and vegetated shorelines, more food) outweigh negative impacts due to increases in nonnative fish abundance?

The GCDAMP Science Advisors articulated the following summary science questions addressed by this project:

- **SA 1.** What are the most limiting factors to successful humpback chub adult recruitment in the mainstem: spawning success, predation on young of year and juveniles, habitat (water, temperature), pathogens, adult maturation, food availability, competition?
- **SA 2.** What are the most probably positive and negative impacts of warming the Colorado River on humpback chub adults and juveniles?

Information Needs Addressed

- **CMIN 2.1.2.** Determine and track recruitment of all life stages, abundance, and distribution of humpback chub in the LCR.
- **RIN 2.2.2.** Determine if a population dynamics model can effectively predict response of native fish under different flow regimes and environmental conditions.
- **RIN 2.2.8.** What combination of dam release patterns and nonnative fish control facilitates successful spawning and recruitment of humpback chub in the Colorado River ecosystem?
- **RIN 2.4.2.** Determine if suppression of nonnative predators and competitors increases native fish populations.
- **RIN 2.4.3.** To what degree, which species, and where in the system are exotic fish a detriment to the existence of native fish through predation or competition?
- **RIN 4.2.5** To what extent is there overlap in the Colorado River ecosystem below the Paria River of RBT habitat and native fish habitat?
- **EIN 2.1.1** How does the abundance and distribution of all size classes of humpback chub in the LCR and mainstem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?

- **EIN 2.1.2** How does the year class strength of humpback chub (51–150 mm) in the LCR and mainstem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?
- **EIN 2.4.1** How does the abundance and distribution of nonnative predatory fish species and their impacts on native fish species in the Colorado River ecosystem change in response to an experiment performed under the Record of Decision, unanticipated event, or other management action?

D. Proposed Work

D.1. Project Elements

Project Element 7.1. Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River

William Persons, Fishery Biologist, USGS, GCMRC
Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office David R. Van Haverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Rogowski, Fisheries Biologist, Arizona Game and Fish Department

The most efficient way to sample adult humpback chub that spawn in the LCR is during the spring as capture probabilities in the LCR for adults are much higher than in the mainstem. Fall sampling provides us with yearly estimates of the abundance of young-of-the-year that have not left the LCR and is the closest we have to a long-term dataset of juvenile humpback chub production. Data collected during these trips are all used to estimate spring and fall closed population abundance for various size classes of humpback chub (> 150 mm and > 200 mm total length (TL)), and during some years provides abundance estimates of other native fishes (Coggins and others, 2006; Van Haverbeke, 2010). The project also marks juvenile humpback chub (< 100 mm TL) with VIE tags in the fall in conjunction with JCM project (Project Element 7.2) and the July LCR marking project (Project Element 7.3) to improve our understanding of juvenile humpback chub production and outmigration. This is an ongoing project since 2000 and the monitoring was identified as a necessary component in the 2011 Environmental Assessment for Non-Native Fish Control Downstream from Glen Canyon Dam and associated Biological Opinion (Bureau of Reclamation, 2011). The specific objectives for 2015–17 (similar to objectives for previous years) are:

1. Determine length stratified Chapman modified Peterson closed population estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm) in the lower 13.57 km of the LCR during the spring and fall.
2. Generate a population estimate of age 0 humpback chub (40-99 mm) during fall.
3. Collect data on PIT tagged fish in support of humpback chub population modelling (Project Element E.10).
4. Collect additional data on fishes in the LCR such as size, species, sexual condition and characteristics, and external parasites (i.e., Lernaea cyprinacea).

Modifications to this project include use of experienced biologists and expansion of remote sensing efforts throughout the LCR (see Project Element 7.4). Specifically, we will replace three volunteer positions with paid staff. This will result in increased salary costs for fiscal years 2015–2017, but reduced travel expenses that had been used for volunteer travel. Working with partners, we propose amalgamation of Arizona Game and Fish Department's (AGFD) lower 1200 meter monitoring efforts into LCR mark-recapture effort (Spring and Fall). This approach avoids the need to increase overall LCR long term monitoring costs due in part to savings associated with fewer helicopter flights and facilitates deployment of portable remote PIT tag readers to assess humpback chub demographics across the three sample reaches constituting the occupied 13 km of the LCR. We also propose to involve Navajo Nation or other Tribal members in sampling activities and have included funding to support a temporary field position (four 10-day trips). Methods will follow those used from 2000-2014 (described in Van Haverbeke and others, 2013). Arizona Game and Fish Department will provide experienced biologists to assist with hoop net efforts, and be responsible for small PIT tag antennas deployed near each camp.

Project Element 7.2. Juvenile Chub Monitoring in the mainstem near the Little Colorado River Confluence

Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.
Maria Dzul, Fishery Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC

This project provides the data to estimate survival, growth and abundance of juvenile humpback chub for a reference reach (RM 63-64.5) in the mainstem Colorado River just downstream of the LCR confluence. It also provides additional passes to estimate rainbow trout and brown trout abundance in this same reach (the reference reach is sampled using rainbow trout specific methods as part of the Natal Origins project; Project Element 9.2). Data from this project, in addition to temperature collected near the LCR confluence through Project 2, will be used in Project Element 7.10 to refine our understanding of the effects of temperature and trout on humpback chub survival and growth. Recent progress in our understanding of trout and mainstem temperature effects on humpback chub population dynamics are solely dependent on data collected through this project and its precursor, the NSE project. Recaptures of VIE marked humpback chub in the reference reach, especially humpback chub marked through the July LCR sampling (Project Element 7.3), are crucial to understanding annual survival and movement out of the LCR into the Colorado River. Obtaining rainbow and brown trout abundance estimates between RM 63-64.5 were identified as necessary activities in the 2011 Environmental Assessment for Non-Native Fish Control Downstream from Glen Canyon Dam and associated Biological Opinion (Bureau of Reclamation, 2011). The metrics are included in the suite of triggers identifying when to implement mechanical removal of nonnative fish to protect humpback chub. Continued annual assessments of juvenile humpback chub survival rates and abundance in the mainstem using methods developed in the NSE Study will provide key metrics by which management actions such as rainbow trout removal will be evaluated.

As with the Natal Origin Research project (Project Element 9.2), the Juvenile Chub Monitoring project is scheduled to be completed by the end of FY2016. This leaves a significant data gap in outlying years for information on juvenile humpback chub as required by the Biological Opinion for Glen Canyon Dam operations including high flow experiments and nonnative fish control (USFWS 2011). To avoid this gap, a transition of the Juvenile Chub Monitoring project from a research focus to a monitoring effort needs to occur while maintaining a robust multi-gear, multi-pass mark-recapture effort necessary to generate reliable survival estimates of these young fish. We propose that GCMRC and its cooperators collaboratively develop a plan for this transition and include it among the topics to be reviewed by the fisheries program protocol evaluation panel (PEP; see Project Element 8.3). The new monitoring project will begin in FY2017 following review and implementation, as appropriate, of the PEP's recommendations by GCMRC.

Project Element 7.3. July Little Colorado River juvenile humpback chub marking to estimate production and outmigration

Maria Dzul, Fishery Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC
Luke Avery, Fishery Biologist, USGS, GCMRC
David Ward, Fishery Biologist, USGS, GCMRC
Mike Yard, Fishery Biologist, USGS, GCMRC

The objective of this project element is to determine how rates of juvenile humpback chub outmigration vary between years and the degree to which outmigration rates are driven by juvenile densities or the strength of flooding associated with summer monsoons. This project also seeks to estimate the abundance of young-of-the-year humpback chub in the LCR prior to the most significant period of outmigration (July-September). As mentioned above, juvenile production and rates of juvenile outmigration are two of the largest uncertainties in population models of humpback chub that spawn in the LCR and thus uncertainty in these population processes hampers efforts to determine how much management is required to maintain healthy adult populations. Uncertainty in juvenile production and outmigration was one of the largest uncertainties in predicting humpback chub responses to alternatives during the LTEMP process. Previous research suggests that rates of outmigration are relatively high (Yackulic and others, 2014). It should be noted, however, that these estimates were based on marks put out only in the lowest portion of the LCR and were concentrated in years that likely had high levels of export (2011 & 2012), thus may have biased estimates high. Preliminary estimates suggest that outmigration by the 2013 cohort was lower and that the size of this cohort may have be relatively small. Lastly, if rates of recovery of juvenile humpback chub marked during July sampling are substantially lower at non-LCR aggregations (Project D) as opposed to in the JCM reach (Project Element E.2) this could be taken as evidence of local reproduction at aggregations.
Sampling during July relies on three gear types, seining, dip nets and hoop nets to capture juvenile humpback chub at each of the three sample reaches and humpback chub between 40-100 mm are given VIE batch marks (humpback chub over 100 mm are scanned for PIT tags according to the standard protocol, however, the focus of our efforts is on juveniles, that is humpback chub under 100 mm in total length).

Project Element 7.4 Remote PIT tag array monitoring

William Persons, Fishery Biologist, USGS, GCMRC

The objectives of this project are to provide data to test hypotheses about trap avoidance and humpback chub movement and to potentially provide a future alternative to decrease handling of adult humpback chub. This has been an ongoing effort since 2009, with lapses and equipment failures during parts of 2010 and 2011. The project has installed two PIT tag antenna arrays in the LCR approximately 2 km upstream from the confluence with the mainstem Colorado River. The antenna arrays read and record PIT tag codes from marked fish along with a date/time stamp as they pass near antennas anchored to the river bottom. These data can be used within population models as well as to provide information on timing of movement and survival of PIT tagged native fishes. Antenna detection efficiency has varied greatly and was estimated to be 6 –

42%. Work completed during FY12–13 by a Colorado State University graduate student is expected to result in a thesis during 2014. Preliminary findings suggests that skip-spawning by adult humpback chub is Markovian (i.e., individuals that spawned in the previous year are less likely to spawn than individuals that did not spawn). During FY2015-17 we plan to maintain the existing antenna arrays and to deploy three portable antennas approximately 9 km upstream from the LCR mouth to attempt to better assess movement and avoidance of hoop nets.

Project Element 7.5. Food web monitoring in the Little Colorado River

Jeff Muehlbauer, Aquatic Ecologist, USGS, GCMRC
Ted Kennedy, Aquatic Ecologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC

The objectives of this project are to characterize invertebrate drift, benthic densities and emergence throughout the perennial (lower 21 km) reach of the LCR over various seasons and to test whether emergence techniques are an appropriate technique for long-term monitoring in this and other tributaries. We suspect that the amount of invertebrates available for consumption by fish, and humpback chub in particular, varies longitudinally because of work suggesting higher humpback chub growth above Chute Falls (Stone and others, *in prep*) as well as higher growth and abundance of subadult humpback chub in Coyote and Salt camps relative to Boulders camp (Dzul and other, *in review*; Vanhaverbeke and others, 2013). Preliminary data collected in July 2013 suggests that emergence below the Chute Falls (no sampling occurred above Chute Falls) increases at stations located further from the confluence. A better understanding of the food base in areas that support high densities of humpback chub growing quickly may aid in determining the carrying capacity within the LCR as well as in tributaries considered for translocation efforts.

This project is a continuation of a project begun in FY13–14. Logistical constraints and weather-related issues ultimately precluded the total completion of this project within that timeframe, and we therefore propose to continue the project into FY15 and possibly the first months of FY 2016 in order to provide better quality results. Sampling will occur quarterly (December, April, June, and September), and monthly in the period of highest humpback chub growth (April to September), with additional opportunistic samples occurring once per year as soon as possible after the first annual summer monsoon flood. Sampling will involve the deployment of sticky traps (Smith and others, 2014) in consistent locations and habitat conditions throughout the perennial 21 km reach of the LCR, from Blue Spring to the confluence with the Colorado River. Light traps (Kennedy and others, 2013) are also set out at camps in the evenings. At the three main camps (Salt, Coyote, Boulders) and at major aquatic habitat changes (Blue Spring, Chute Falls, confluence), benthic samples are also taken using standard D-nets, emergence traps are deployed over the water, infall traps for organic matter and terrestrial insects are deployed at the water's edge, and aquatic habitat is quantified based on visual estimates of percent cover of algae and using pebble counts (Wolman, 1954). Finally, temperature, conductivity, and dissolved oxygen are measured using data loggers deployed above and below the Chute Falls/Atomizer complex and near Salt and Coyote camps.

Project Element 7.6. Potential for gravel substrate limitation for humpback chub reproduction in the LCR

Maria Dzul, Fishery Biologist, USGS, GCMRC
Jeff Muehlbauer, Aquatic Ecologist, USGS, GCMRC
David Ward, Fishery Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC

The objectives of this project element are to characterize year-to-year variation in gravel availability in the LCR and determine whether lack of gravels limits juvenile humpback chub production in certain years. VanHaverbeke and others (2013) showed that juvenile humpback chub production in the LCR has been lower during the period 2001–2012 during years without significant winter/spring flooding. Earlier work suggested that increases in discharge in the LCR exposes fresh gravel deposits that are ideal for development of humpback chub eggs (Kaeding and Zimmerman 1983) and that humpback chub spawning activity is associated with clean gravel deposits (Gorman and Stone 1999). Accordingly, scarcity of gravel substrates may play a significant role in humpback chub population processes, however, there is little direct evidence to determine whether the cause of low recruitment is due to scarcity of fresh gravel deposits. Evaluating how low spring discharge affects humpback chub recruitment is especially important because climate projections predict decreased precipitation throughout the southwestern USA (Seager and others 2007), and thus years with low snowmelt may become increasingly common in northern Arizona. This project will involve annual substrate mapping and monitoring using bed surface random-walk pebble counts (Wolman 1954) in a reference reach of the LCR conducted every year in conjunction with spring LCR monitoring (Project Element 7.1). In addition, we will conduct gravel tray experiments to determine the sediment characteristics that are required for humpback chub egg deposition and survival.

Project Element 7.7. Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River

David Ward, Fishery Biologist, USGS, GCMRC
Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office

The objective of this project is to evaluate the extent to which high levels of dissolved CO_2 in the LCR at base flow impacts early life history stages of humpback chub. High levels of dissolved CO_2 in water are known to negatively affect fish populations and have been hypothesized to constrain humpback chub to the lower 14.2 km of the LCR in Grand Canyon (Mattes 1993, Robinson and others 1996, Kaeding and Zimmerman 1983). Elevated CO_2 levels decrease the ability of a fish's hemoglobin to transport oxygen and can compromise respiration in fishes. The safe or accepted levels of CO_2in water depend upon fish species (Basu 1959). In general, levels above 60 ppm are avoided by fish and can be detrimental to fish health (Alabaster and others 1957, Reviewed in Heinen and others 1996) with early life history stages of fish being most sensitive (Baumann and others 2012). At base flow CO_2 levels near the confluence of the LCR are often above 100 ppm and increase upstream (Robinson and others 1996, Dennis Stone FWS, personal communication). Such high levels of CO_2 have the potential to structure the fish community within the LCR, but little is known about CO_2 tolerances of humpback chub or other native Colorado River fishes. Measures of upper lethal CO_2 tolerances will be made in the laboratory for all fish species commonly found within the LCR and for invasive nonnative fishes that could become established within the LCR. Both adult and juvenile life stages will be evaluated. Captive reared humpback chub from the Southwestern Native Aquatic Research and

Recovery Center in Dexter New Mexico will be utilized for these studies. All other species will be captured from the LCR in Grand Canyon.

Project Element 7.8. Evaluate effects of Asian tapeworm infestation on juvenile humpback chub

David Ward, Fishery Biologist, USGS, GCMRC

The objective of this project is to monitor the extent of Asian fish tapeworm (*Bothriocephalus acheilognathi*) infestation in juvenile humpback chub annually in the LCR and assess potential impacts to humpback chub populations. Asian fish tapeworm has been identified as one of six potential threats to the continued persistence of endangered humpback chub (USFWS 2002). It is potentially fatal to multiple age classes of fish (Schäpperclaus 1986), and has caused high mortality when infecting new host species (Hoffman and Schubert 1984). Asian fish tapeworm was first documented in the LCR in Grand Canyon in 1990 (Minckley 1996) and is hypothesized to be a cause of long-term declines in condition of adult humpback chub from the LCR (Meretsky and others 2000). The life cycle of Asian fish tapeworm is highly temperature dependent (Granth and Esch 1983) and management options aimed at increasing mainstem Colorado River water temperatures may permit Asian tapeworm to increase in number and range with detrimental effects to humpback chub. Monitoring is needed since no baseline information for tapeworm infestation in humpback chub is available. USFWS captures juvenile humpback chub from the LCR each summer prior to monsoon flooding for translocation into Grand Canyon tributary streams such as Shinumo Creek and Havasu Creek. These fish are held at the U.S. Fish and Wildlife Service Southwest Native Aquatic Research and Recover Center (SNARRC) in Dexter, New Mexico prior to being PIT tagged and translocated. They are treated with Praziquantel to remove Asian Tapeworm as part of this process but no efforts have been made to quantify tapeworm loads in these fish. We propose to non-lethally quantify tapeworm loads (Ward 2007) on an annual basis from humpback chub collected for translocation. Our objectives are to establish a baseline of tapeworm infestation levels in LCR humpback chub and to determine whether year-to-year variation in the prevalence of tapeworm infestation is linked to annual variation in growth, survival or abundance of juvenile humpback chub.

Project Element 7.9. Development of a Non-Lethal Tool to Assess the Physiological Condition of Humpback Chub in the Colorado and Little Colorado Rivers

Kimberly Dibble, Research Biologist, USGS, GCMRC
Mike Yard, Fishery Biologist, USGS, GCMRC
David Ward, Fishery Biologist, USGS, GCMRC

This research focuses on laboratory work to test the feasibility of a more sensitive technique to assess the condition of native fish, which could then be used in the field as a non-lethal tool to monitor the health and condition of fish residing in mainstem aggregations and in the LCR. Past research studies using length-weight relationships and recapture data have observed differences in fish condition and growth between fish residing in the mainstem vs. the LCR. Findings have shown periodic and seasonal declines in adult humpback chub condition, where fish recovered more rapidly in the Colorado River than those remaining in the LCR (Meretsky and others 2000). Similar patterns have also been observed for juvenile humpback chub growth rates (Finch and others 2013; Hayes and others, unpublished data), findings that are of concern because of implications to humpback chub survival. However, these length/weight relationships may not provide an accurate assessment of the true physiological condition of fish because relationships change through ontogeny and seasonally (Bolger and Connolly 1989, Cone 1989, Simpkins and others 2003, Froese 2006), and weights may be overinflated due to ova (eggs), parasites, hydrated tissues (water gain following lipid loss), and/or instrument error, especially for small fish. Further, high summer growth of humpback chub in the LCR followed by low growth in early fall suggests that the energy allocation strategy of these fish shifts toward fat storage in preparation for winter rather than somatic growth (length or weight gain). Investment into lipid storage would increase the condition of humpback chub, but this is not reflected in growth analyses. Therefore, humpback chub monitoring of growth and condition would be improved through the development of a tool in the laboratory to assess the condition of native fish, which would eventually be incorporated into field monitoring efforts.

Bioelectrical Impedance Analysis (BIA) is a tool that has been successfully developed for cyprinids and other fish species (e.g., common carp (*Cyprinus carpio*), brook trout (*Salvelinus fontinalis*), cobia (*Rachycentron canadum*), steelhead (*Oncorhynchus mykiss*)) in both freshwater and marine ecosystems (Cox and Hartman 2005, Duncan and others 2007, Hanson and others 2010, Klefoth and others 2013); however, this technique has not been refined for native cyprinids such as humpback chub, roundtail chub (*Gila robusta*), or sucker species of interest in the Colorado River basin. BIA measures body condition and is based on the technology used by humans to estimate percentages of body fat and water when they step on an at-home digital scale. A low-level, safe, electrical current is passed through the human body (or fish body), and the level of “impedance” is measured. Fat offers more resistance to electrical current than water, so a human (or fish) that has a higher fat content will score higher on the impedance scale. For fish, a higher impedance reading correlates to better condition and indicates the fish is more likely to survive periods of low food availability, disease outbreaks, successfully reproduce the following spring, and cope with environmental perturbations.

The temperature of the water in which a fish resides can significantly influence BIA readings (Klefoth and others 2013), so we will develop a suite of experimental treatments in the laboratory where temperature and food rations can be controlled. Throughout each experiment, repeated measures of impedance in hatchery-raised humpback chub and/or surrogate species (e.g., roundtail chub, bonytail (*Gila elegans*)) of varying lengths will be quantified using a Quantum IV Body Composition Analyzer. Relationships between impedance readings and proximate body composition (percent lipid, protein, carbohydrate, water, ash) of sacrificed fish from laboratory experiments will allow us to calibrate the models for use in subsequent field monitoring (we need this calibration to verify the BIA analyzer is accurately characterizing the condition of native fish species). Since we need to develop these relationships for multiple species of varying lengths, this project will occur in several phases over 3 years to allow hatchery fish to grow to the size of comparable fish in the field.

Project Element 7.10. Humpback chub population modelling

Charles B. Yackulic, Research Statistician, USGS, GCMRC
Maria Dzul, Fishery Biologist, USGS, GCMRC

The ultimate objective of this project is to provide better tools to understand the current state of the humpback chub resource (i.e., adult population size) and to predict its future state in response to management decisions. In some instances, better prediction will come mainly through the incorporation of more data (e.g., additional JCM data will help determine whether trout and temperature relationships developed for the LTEMP model hold), whereas other instances require substantial intellectual investment into building appropriate statistical models (e.g., efforts to incorporate data collected through remote sensors (Project Element 7.4) with data collected through mark-recapture techniques (Project Elements 7.1-3)). One area of emphasis in FY15–17 will be on better estimation of juvenile humpback chub production and outmigration, as well as on potential mechanisms that may explain year to year variation in these population processes. Another area of emphasis will be on further clarifying relationships between temperature, trout abundances and juvenile humpback chub population biology in the mainstem. Specific attention will be placed on publishing statistical models used to link temperature and rainbow trout analyses to humpback chub growth and survival for the LTEMP process as well as exploring the implications of these results for triggering management actions like mechanical removal of nonnative fishes. We can also envision modifying these models to jointly model rainbow trout abundance and humpback chub survival to provide more accurate estimates of uncertainty. A third area of emphasis will be on testing hypotheses about adult humpback chub capture probability and movement.

D.2 Personnel and Collaborations

The overall project lead for Research Project 7.0 is Dr. Charles Yackulic, a research statistician with U.S. Geological Survey, Grand Canyon Monitoring and Research Center (GCMRC), who specializes in population dynamics and modeling. Kirk Young, Randy VanHaverbeke, and Dennis Stone are fishery biologists with the U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office that collect and analyze fishery data from annual spring and fall mark-recapture studies conducted in the LCR. Bill Persons, a fishery biologist at GCMRC is responsible for database management, analysis, and remote PIT tag array monitoring in the LCR. Dr. Kim Dibble is a post-doctoral fellow and research biologist at GCMRC with expertise in fish physiology and metadata analysis. Maria Dzul is a fishery biologist (GCMRC) that specializes in data collection, modeling and data analysis of HBC production and movement. David Ward is a fishery biologist (GCMRC) that maintains and operates the experimental laboratory facility at Northern Arizona University. He has expertise in experimental physiology with an emphasis on non-native and native fish interactions. Dr. Jeff Muehlbauer is a post-doctoral fellow and research biologist at GCMRC with expertise in ecology and life history of aquatic macro-invertebrates. Dr. David Rogowski is a fishery biologist with Arizona Game and Fish Department and is the principal investigator that collects, provides, and analyzes data as part of the SWEF project (6.4). Dr. Josh Korman with Ecometric Research Inc. and Dr. Michael Yard with (GCMRC) are co-investigators on the Natal Origin Project (9.2) that provide the necessary field data from the Colorado River mainstem for the JCM project.

D.3 Deliverables

The work described here should lead to multiple peer-reviewed publications (i.e., at least 4), as well as annual reports and presentations to the GCDAMP. This project will also provide estimates of quantities relevant to biological opinions at regular intervals.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

By the end of FY13–14, FWS LCR system-wide sampling will have occurred four times in each year, JCM sampling will have occurred four times in each year, and July LCR juvenile marking will have occurred once per year. All data from these trips has or will be entered into the GCMRC fish database.

E.2. Completed Publications

Van Haverbeke, D. R., D. M. Stone, L. G. Coggins, and M. J. Pillow. 2013. Long-Term Monitoring of an Endangered Desert Fish and Factors Influencing Population Dynamics. Journal of Fish and Wildlife Management 4:163-177.

Yackulic, C. B., M. D. Yard, J. Korman, and D. R. Van Haverbeke. 2014. A quantitative life history of endangered humpback chub that spawn in the Little Colorado River: variation in movement, growth, and survival. Ecology and Evolution 4:1006-1018.

E.3. Publications in progress

Dodrill, M., C. B. Yackulic, B. Gerig, W. E. Pine, III, J. Korman, C. Finch *in review.* Do Management Actions to Restore Rare Habitat Benefit Native Fish Conservation? Distribution of Juvenile Native Fish among Shoreline Habitats of the Colorado River. *River Research and Applications*

Dzul, M., C. B. Yackulic, D. M. Stone, D. R. Van Haverbeke *in review*. Survival, growth, and movement of age 1-2 humpback chub, Gila cypha, in the Little Colorado River, Arizona. *River Research and Applications*

Ward, D.L. and others. *In review.* A laboratory evaluation of tagging related mortality and tag loss in juvenile humpback chub, Gila cypha. *North American Journal of Fisheries Management.*

Ward, D.L. and R. Morton-Starner. *In prep*. Effects of water temperature and fish size on predation vulnerability of humpback chub to rainbow and brown trout.

Yackulic, C. B. and others. *In prep*. Vital rate estimation sheds light on the relative importance of altered habitat and introduced rainbow trout in the decline and recovery of an endangered fish, humpback chub.

E.4. Presentations at GCDAMP meetings

Dzul and others (2014) Variation in vital rates of age 1 humpback chub Gila cypha in the Little Colorado River. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER – TWG and AMWG meetings.

Morton-Starner, R. and D.L. Ward (2014). An experimental evaluation of competition between rainbow trout and humpback chub. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER.

Yackulic C.B. and others (2013) Recent advances in population modeling, preliminary estimates, and their relevance to BO triggers. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. PRESENTATION – TWG.

Yackulic C.B. and others (2014) Results from Colorado River Study Site and ongoing population modeling. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. PRESENTATION – TWG.

Yackulic C.B. and others (2014) LTEMP modelling results for humpback chub and trout. LTEMP stakeholders workshop, Phoenix, AZ. PRESENTATION – LTEMP.

Yackulic C.B. and others (2014) LTEMP modelling results for humpback chub and trout and follow up. LTEMP Consensus discussions, Phoenix, AZ. PRESENTATION – LTEMP.

Ward, D.L. and R. Morton-Starner (2014). Effects of water temperature and fish size on predation vulnerability of humpback chub to rainbow and brown trout. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER – TWG and AMWG meetings.

E.5. Presentations at professional meetings

Dzul M. and others (2013) Assessing variation through space and time in the vital rates of humpback chub in the Little Colorado River. Desert Fishes Council – Flagstaff, AZ.

Dzul M. and others (2014) Spatial and temporal variation in vital rates of an endangered fish in a desert stream. Ecological Society of Ameria – Sacramento, CA.

Morton-Starner, R. and D.L. Ward (2014). An experimental evaluation of competition between rainbow trout and humpback chub. Desert Fishes Council – Flagstaff, AZ.

Yackulic C.B. and others (2012) Movement and growth in humpback chub: Using multistate models for inference from a mixed batch and individual tag dataset. Ecological Society of America – Portland, OR.

Yackulic C.B. and others (2013) Variation in vital rates in a doubly partially migratory system: Humpback chub in the lower Colorado River. Euring Analytical conference – Athens, GA.

Yackulic C.B. and others (2013) Disentangling residency and migration in a partial migratory system where detection is much less than one. Ecological Society of America – Minneapolis, MN.

Yackulic C.B. and others (2013) A quantitative life history of humpback chub that spawn in the Little Colorado River: variation in movement, growth and survival. Desert Fishes Council – Flagstaff, AZ.

Ward, D.L. and R. Morton-Starner. Effects of water temperature and turbidity on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout. Desert Fishes Council – Flagstaff, AZ.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$508,600**	**$15,000**	**$61,100**	**$262,300**	**$555,000**	**$0**	**$149,100**	**$1,551,100**
X							7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$23,200	$0	$15,500	$90,800	$370,000	$0	$31,300	$530,800
X							7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$93,600	$0	$8,900	$135,800	$170,000	$0	$42,400	$450,700
				X			7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$62,500	$4,000	$5,400	$24,800	$0	$0	$15,100	$111,800
X							7.4	Remote PIT tag array monitoring in the LCR	Persons	$34,700	$0	$3,500	$3,600	$5,000	$0	$6,700	$53,500
				X			7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$114,800	$2,000	$1,000	$4,200	$0	$0	$19,100	$141,100
				X			7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,400	$500	$1,000	$3,100	$0	$0	$1,600	$11,600
				X			7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$53,500	$3,000	$17,500	$0	$10,000	$0	$11,900	$95,900
X							7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,000	$2,000	$1,500	$0	$0	$0	$2,300	$16,800
		X					7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$27,900	$1,500	$6,700	$0	$0	$0	$5,600	$41,700
X			X				7.10	Humpback chub population modelling	Yackulic and Dzul	$82,000	$2,000	$100	$0	$0	$0	$13,100	$97,200

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY16																	
							7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$603,400**	**$13,300**	**$52,400**	**$267,900**	**$555,000**	**$0**	**$216,600**	**$1,708,600**
X							7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$26,900	$0	$8,300	$98,100	$370,000	$0	$39,500	$542,800
X							7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$96,700	$0	$9,000	$135,800	$170,000	$0	$56,600	$468,100
				X			7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$60,900	$4,000	$5,300	$26,800	$0	$0	$20,700	$117,700
X							7.4	Remote PIT tag array monitoring in the LCR	Persons	$79,900	$0	$3,500	$3,900	$5,000	$0	$18,800	$111,100
				X			7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$70,000	$2,000	$0	$0	$0	$0	$15,400	$87,400
				X			7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,600	$300	$1,000	$3,300	$0	$0	$2,200	$12,400
				X			7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$59,500	$3,000	$18,000	$0	$10,000	$0	$17,500	$108,000
X							7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,300	$2,000	$500	$0	$0	$0	$2,900	$16,700
		X					7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$71,600	$0	$6,700	$0	$0	$0	$16,700	$95,000
X			X				7.10	Humpback chub population modelling	Yackulic and Dzul	$121,000	$2,000	$100	$0	$0	$0	$26,300	$149,400

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
							7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$587,000**	**$13,300**	**$52,500**	**$168,200**	**$435,000**	**$0**	**$237,700**	**$1,493,700**
X							7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$22,400	$0	$8,400	$105,300	$370,000	$0	$48,400	$554,500
X							7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$67,100	$0	$9,000	$26,300	$50,000	$0	$29,500	$181,900
				X			7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$63,600	$4,000	$5,300	$28,800	$0	$0	$27,800	$129,500
X							7.4	Remote PIT tag array monitoring in the LCR	Persons	$108,000	$0	$3,500	$4,200	$5,000	$0	$31,800	$152,500
				X			7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$0	$2,000	$0	$0	$0	$0	$500	$2,500
				X			7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,900	$300	$1,000	$3,600	$0	$0	$3,000	$13,800
				X			7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$71,400	$3,000	$18,000	$0	$10,000	$0	$25,600	$128,000
X							7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,900	$2,000	$500	$0	$0	$0	$3,900	$18,300
		X					7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$74,400	$0	$6,700	$0	$0	$0	$22,200	$103,300
X			X				7.10	Humpback chub population modelling	Yackulic and Dzul	$162,300	$2,000	$100	$0	$0	$0	$45,000	$209,400

Project 8. Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon

Initial Estimate: FY15: $184,500; FY16: $226,500; FY17: $296,100

GCDAMP Funding: FY15: $184,500; FY16: $210,600; FY17: $281,300

A. Investigators

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B. Project Summary

This project encompasses two ongoing management actions and two new projects, all designed to increase survival of juvenile native fishes in Grand Canyon. In addition, we propose to convene a protocol evaluation panel comprised of external experts to conduct a review of the fisheries research, monitoring, and management actions conducted in support of the Glen Canyon Dam Adaptive Management Program (GCDAMP). In FY15–17 we will continue ongoing mechanical removal of rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) using electrofishing near the confluence of Bright Angel creek, in support of Grand Canyon National Park's goals to reduce nonnative fish abundance in and around Bright Angel Creek for the benefit of juvenile native fish. We will also continue to translocate juvenile humpback chub (*Gila cypha*) annually from the Little Colorado River (LCR) into areas within the LCR and continue to support translocation efforts into Havasu Creek and Shinumo Creek, to increase survival and distribution of humpback chub. In FY16 or FY17 we will participate in a review by external experts of these activities and other fisheries projects (see Projects 6, 7, and 9). The review of Project 8 activities will emphasize evaluation of the effectiveness of these experimental actions in meeting GCDAMP or National Park Service (NPS) goals and objectives as appropriate, and the panelists will be asked to make recommendations as to how projects can be adapted to meet project goals and objectives and whether the continuation of these efforts are warranted in future years. NPS will also consider the review panel's recommendations, but any changes in implementation are under the discretion of the NPS consistent with the Comprehensive Fish Management Plan for Grand Canyon National Park (NPS, 2013). This project also includes two new project elements that will inform future potential management actions: 1). An assessment of invasive aquatic species within the LCR drainage, to evaluate potential risks to humpback chub populations and 2.) Genetic monitoring of humpback chub to confirm that ongoing management activities do not have detrimental effects on the genetics of the Grand Canyon population of this endangered species.

C. Background

Fish populations are typically limited by survival and recruitment of juvenile fish (Myers 1995). Endangered humpback chub in Grand Canyon are also believed to be limited by survival and recruitment of juvenile fish (Coggins and Walters, 2009; Hayden and others, 2012; Limburg and others, 2013). Management actions for humpback chub have focused on trying to reduce predation mortality of juvenile fish by either mechanically removing predatory trout from the mainstem Colorado River, or by translocating juvenile humpback chub from the lower LCR into other areas to improve growth and subsequent survival. Predation mortality in fish is highly size dependent with smaller fish being much more vulnerable to predation than larger individuals (Bailey and Houde, 1989). Increases in growth rate generally leads to higher survival and less predation mortality (Tonn and Paszkowski, 1992). These general patterns are also true for humpback chub in Grand Canyon (Ward and Morton-Starner, *in prep*). Translocation of juvenile humpback chub from the LCR into other areas with lower fish densities and higher food abundance is one way to increase growth rates and potentially increase subsequent survival. Experimental actions to benefit native fishes that were funded in the USGS Grand Canyon Monitoring and Research Center's FY13–14 workplan included a collaborative effort with the National Park Service (NPS) to mechanically remove trout from the Colorado River mainstem near the confluence of Bright Angel Creek and a U.S. Fish and Wildlife Service led project to translocate juvenile humpback chub from the LCR into areas above the Chute/Atomizer Falls complex, within the LCR. Support was also provided for NPS efforts to collect juvenile humpback chub from the LCR for translocation into Shinumo and Havasu Creeks.

C.1. Management Background

Humpback chub have declined in both abundance and distribution likely because of interactions with nonnative species and the alteration of flow and temperature regimes caused by construction and operation of Glen Canyon Dam (Minckley and Marsh, 2009). Introduced rainbow trout and brown trout are known to prey upon juvenile native fish, including humpback chub, in Grand Canyon (Yard and others, 2011). Predation by these nonnative species may adversely affect native fishes at a population level. To reduce potential predation on humpback chub, electrofishing was used to mechanically remove nonnative fish from the Colorado River near the confluence with the LCR, from 2003–2006, and again in 2009 (Coggins and others, 2011). Humpback chub abundance increased following removal efforts, but system-wide decreases in rainbow trout and drought induced increases in water temperature occurred during the same period making it difficult to determine which factors were responsible for increased native fish abundance (Coggins and others, 2011).

Brown trout are of particular concern for native fishes in Grand Canyon because of their highly piscivorous nature (Yard and others, 2011, Ward and Morton-Starner, *in prep*, Whiting et al. 2014). The highest densities of brown trout in Grand Canyon occur in or near Bright Angel Creek (Makinster and others, 2010). Large numbers of brown trout in this area may be limiting native fish abundance, including humpback chub, locally as well as downstream. This idea is based on the hypothesis that most of the humpback chub inhabiting western Grand Canyon are produced within the LCR and disperse downstream. If the bottleneck to dispersal and recruitment of humpback chub or other native fish species in western Grand Canyon is occurring near the confluence of Bright Angel Creek because of brown trout predation, then removing brown trout from this area could increase the number of native fish that inhabit downstream reaches. Removal of rainbow trout and brown trout in the mainstem Colorado River near the confluence of Bright Angel Creek occurred in 2013. The effectiveness of this experimental action cannot be adequately evaluated without at least two to three more years of removal effort so is planned to occur in FY15-17. The 2013 High Flow Experiment (HFE) caused mechanical removal efforts at Bright Angel Creek to be reduced from 10 depletions to 5 depletions, and high turbidity throughout much of the removal effort reduced capture efficiency significantly such that only 1,851 fish were removed (Nelson and others, 2014). The possibility of another HFE in November 2014 led us to reconsider the timing of removals in FY15 and begin discussions with the National Park Service to conduct this action later in the fiscal year. Mainstem mechanical removal of nonnative fish near the confluence of the LCR is a prescriptive management action that is only implemented when a set of criteria outlined in the 2011 Biological Opinion for Operation of Glen Canyon Dam (U.S. Fish and Wildlife Service, 2011) are met, but mainstem mechanical removal near the confluence of Bright Angel Creek is being evaluated as an experimental action as described in the Comprehensive Fisheries Management Plan for Grand Canyon National Park (NPS, 2013).

Efforts to translocate humpback chub upstream of Chute Falls in the LCR and to monitor their status have been ongoing annually since 2003. Approximately 2,363 juvenile (70-130 mm total length; TL) humpback chub have been translocated upstream of Chute Falls through 2013. In 2003, the action was identified as a voluntary conservation action to offset potential impacts on humpback chub from proposed experimental releases from Glen Canyon Dam and mainstem mechanical removal of nonnative fish. Since 2012, translocation and monitoring efforts of humpback chub in this upper portion of the LCR corridor have been incorporated as a conservation measure in the recent Final Biological Opinion on the Operation of Glen Canyon Dam (U.S. Fish and Wildlife Service, 2011).

C.2 Key Monitoring and Research Questions Addressed in this Project

This project addresses two Adaptive Management Work Group (AMWG) priority Questions 1: Why are humpback chub not thriving? and 2: What are the most limiting factors to successful humpback chub adult recruitment in the mainstem Colorado River?

This project directly addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), Science advisory summary questions (SA), and Research Information Needs (RINs) previously identified by the GCDAMP in the 2007 Grand Canyon Monitoring and Research Plan:

Primary SSQ addressed:

- SSQB2. What are the most effective strategies and control methods to limit nonnative fish predation on, and competition with native fishes?

Primary Core Monitoring Information Needs addressed:

- CMIN SA 1. Which of the following are the most limiting factors to successful HBC adult recruitment in the mainstem: spawning success, predation on YoY and juveniles, habitat (water, temperature), pathogens, adult maturation, food availability, or competition?

Research Information Needs addressed:

- RIN 2.4. To what degree, which species, and where in the system are exotic fish a detriment to the existence of native fish through predation or competition?

This project will answer the following key questions about impacts of nonnative fish on native fish within Grand Canyon:

1. What is the efficacy and feasibility of using electrofishing to control brown trout populations through a coordinated mainstem and tributary removal effort in and around Bright Angel Creek.
2. Does brown trout removal have a measurable positive effect on native fish abundance and distribution in the mainstem near Bright Angel Creek or within Bright Angel Creek?
3. Can translocation of Juvenile Humpback chub from the Little Colorado River into uninhabited locations increase survival and recruitment of juvenile chub?

D. Proposed Work

D.1. Project Elements

Project Element 8.1. Efficacy and Ecological Impacts of Trout Removal at Bright Angel Creek

David Ward, Fishery Biologist, USGS, GCMRC
Mike Yard, Fishery Biologist, USGS, GCMRC
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
Emily Omana, Fishery Biologist, NPS, Grand Canyon National Park
Clay Nelson, Fishery Biologist, NPS, Grand Canyon National Park

The objective of this project is to evaluate the feasibility and efficacy of mechanical (electrofishing) trout removal in meeting NPS management goals for Bright Angel Creek and the Bright Angel Creek inflow reach, and to assess the response of native fish to trout removal. This project is being conducted in close collaboration with Grand Canyon National Park, consistent with the NPS Comprehensive Fisheries Management Plan and related compliance documents. The mainstem trout removal treatment is part of a multi-year, comprehensive experimental trout removal treatment using mechanical removal that began in 2013. This treatment will be applied to the mainstem Colorado River and will complement ongoing NPS efforts in Bright Angel Creek (i.e., weir operation and electrofishing). The objective is to significantly reduce trout abundance by 80% (NPS 2013). Removal in the Colorado River mainstem will occur in a 8.45 km (5.25 mile) reach of Upper Granite Gorge (river miles 85 to 90) using electrofishing depletion methods similar to those used from 2003 to 2006 at the confluence of the LCR (Coggins and others, 2011). Electrofishing removals on the mainstem Colorado River will occur during the fall-winter season concurrent with weir and multi-pass backpack electrofishing operations within Bright Angel Creek from October to March. Efforts in the mainstem will consist of 5 to 10-pass depletions with a single pass occurring over the entire study area in two nights (amount of effort based on calculated capture probabilities with a goal of 75% reduction in trout numbers). It has been estimated that each trip will consist of 10-20 nights of sampling. All electrofishing will be conducted at night using two 16' sport boats outfitted for electrofishing with a Coffelt® or equivalent CPS unit with one netter per boat. Large numbers of trout (> 2,000 fish) are likely to be removed. These fish will be put to beneficial use as described in the Comprehensive Fish Management Plan for Grand Canyon National Park (NPS, 2013), and pursuant to the Memorandum of Agreement (MOA) between the NPS and Arizona State Historic Preservation Officer, and through continued consultation with Traditionally Associated Tribes. To determine efficacy and ecological consequences of trout removal, densities and conditions of native fishes will be monitored by NPS and the USGS Grand Canyon Monitoring and Research Center (GCMRC) in Bright Angel Creek and the Bright Angel Inflow reach. Continued native fish monitoring (see Project Element 6.4), both within the removal area and in other areas downstream, are needed to assess if increased dispersal of native fish is occurring as a result of removal efforts. This project was initiated in 2013–2014 (Nelson and others, 2014) and we propose that this experimental management action be continued in FY15 with possible extension through FY17.

Project Element 8.2. Translocation and monitoring of Humpback chub above Chute Falls in the Little Colorado River

Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
D. R. VanHaverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
William Persons, Fishery Biologist, USGS, GCMRC

The objective of this project is to increase the survival of up to 1,000 juvenile humpback chub annually by translocating them from the lower Little Colorado River (LCR) into areas above the Chute /Atomizer Falls complex in the LCR or into Shinumo Creek or Havasu Creeks. These locations all have low densities of large-bodied fish and high food abundance (Robinson and others 1996; Spurgeon, 2012), which would presumably lead to increased growth rates and higher likelihood of survival. In the December 2002 and November 2004 Biological Opinions on the proposed experimental releases from Glen Canyon Dam and removal of nonnative fish within the Colorado River, a conservation action was identified to relocate approximately 300 humpback chub (50-100 mm TL) in 2003 and 2004, and another 600 fish in 2005 from near the LCR confluence to an upstream LCR reach above Chute Falls that was previously unoccupied by this species. Additional translocations ensued following the recommendations of other Biological Opinions. Translocation and monitoring efforts of humpback chub in this upper portion of the LCR corridor have since been incorporated as a conservation measure in the recent Final Biological Opinion on the Operation of Glen Canyon Dam Including High Flow Experiments and Non-Native Fish Control (U.S. Fish and Wildlife Service, 2011). Through 2013, 2,363 juvenile (50–130 mm TL) humpback chub have been translocated upstream of Chute Falls (Stone and others, *in prep*). From 2003 to 2013, 777 unique humpback chub (i.e., counted only once) have been captured above Chute Falls, of which 369 were adults (≥ 200 mm). Additionally, 1,540 unique humpback chub (893 were ≥ 200 mm) were captured directly downriver in the small 0.5 km Atomizer reach. The rapid growth rates of humpback chub in these two reaches may have resulted in many individuals losing their elastomer tags before they were recaptured, making it difficult to distinguish the provenance of many of these fish (i.e., translocated, progeny, or upriver migrants); however, all humpback chub translocated since 2008 have been PIT-tagged before being released. From 2006 to 2009, two-pass mark recapture population estimates of humpback chub were conducted annually in the Atomizer reach and above Chute Falls, after which capture probabilities have been used to estimate the populations. Monitoring will continue to occur during the spring, prior to monsoon flooding to evaluate the retention and growth rates of translocated humpback chub.

Project Element 8.3.Glen Canyon Dam Adaptive Management Program Fisheries Research, Monitoring, and Management Actions Protocol Evaluation Panel

Scott VanderKooi, Supervisory Biologist, USGS, GCMRC
Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
David Rogowski, Fisheries Biologist, Arizona Game and Fish Department

An external review panel comprised of scientists with relevant expertise will be convened in either FY16 or FY17 to ensure that the quality and relevance of fisheries science being conducted by GCMRC and its cooperators is held to the highest of standards. This panel will conduct a review of all aspects of the GCRMC fisheries program described in Projects 6, 7, 8, and 9 of the FY15–17 workplan. They will make recommendations regarding the scope and direction of the program as well as provide an evaluation and recommendations for future work with respect to the level of effort, study design, and relevance of individual research activities.

Project Element 8.4. Little Colorado River Invasive Aquatic Species Surveillance

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Ward, Fishery Biologist, USGS, GCMRC
Bill Persons, Fishery Biologist, USGS, GCMRC
David Rogowski, Fisheries Biologist, AGFD

The objective of this project is to identify surveillance sites within the LCR basin upstream of Grand Canyon that can provide early detection and response for emerging deleterious invasive aquatic species within the LCR drainage. If invasive species deleterious to humpback chub are detected, we will develop and implement a rapid response plan. In Arizona, dozens of aquatic invasive species have been introduced (fish, mollusks, crustaceans), have expanded distributional ranges, and pose a growing threat to native aquatic species. The first line of defense for reducing the impact from invasive species is preventing their introduction and establishment. Multiple management agencies, notably state wildlife agencies, maintain active invasive species prevention programs. Even the best prevention efforts cannot stop all invasive species, and thus, early detection, rapid assessment and Rapid Response actions represent a critical second defense.

In Grand Canyon, the LCR is the largest tributary and primary spawning ground for humpback chub, however, the species is limited to the lower 15 km of the system (Douglas and Marsh, 1996; Gorman and Stone, 1999). The LCR encompasses a basin of about 8,100 m^2 in eastern Arizona and western New Mexico, with its perennial headwaters arising near Mt. Baldy, Arizona. Estimates of surface water supply and contemporary cultural depletions by the Arizona Department of Water Resources (1989; 1990; 1994) feed approximately 95 reservoirs and 3,700 stock tanks. Reservoirs and stock tanks are potential sources of invasive species and many drain into the LCR or its tributaries. Large quantities of human derived debris in the LCR in Grand Canyon illustrate the connectivity of the river in Grand Canyon to upper portions of the watershed. Biological connectivity also exists based on the capture of red shiner (*Cyprinella lutrensis*), common carp (*Cyprinus carpio*), fathead minnow (*Pimephales promelas*), black bullhead (*Ameiurus melas*), and plains killifish (*Fundulus zebrinus*) at Grand Falls, all thought to have originated hundreds of kilometers upstream (Stone and others, 2007). Conservation success of humpback chub in the LCR and Grand Canyon is vulnerable to incursion by invasive aquatic species from upstream.

A Reasonable and Prudent Alternative in the 1995 EIS was to protect humpback chub in the LCR by development of a LCR Management Plan (USBR, 1995). A final draft of the plan was completed in 2008 (Valdez and Thomas, 2009). This study will augment that plan by providing specific information and data concerning sources of non-native fish within the LCR basin. Surveillance sites will be assessed based on their likelihood to concentrate/harbor species, watershed/sub-watershed reference location, accessibility, ability to be sampled. From 6–12 sites will be sampled annually in May-June using passive (entanglement nets, hoop nets) and active (seines, electrofishers) gears as appropriate.

Project Element 8.5. Genetic monitoring of Humpback chub in Grand Canyon

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office Bill Persons, Fishery Biologist, USGS, GCMRC
Wade Wilson, Geneticist, USFWS, Southwest Native Aquatic Resources Research and Recovery Center

The objectives of this project are to monitor genetic changes in the Grand Canyon population of humpback chub that may result because of ongoing management activities such as translocations. Humpback chub management actions in the lower basin of the Colorado River include annual population monitoring, translocations to Shinumo Creek, Havasu Creek, and the Chute Falls area of the LCR. In 2008, a refuge population was started at the USFWS Southwest Native Aquatic Resources Research and Recovery Center. As a result of these ongoing management actions, a small set of fin clip samples (about 30 per reach in the LCR) were taken to establish baseline genetic data in the LCR. An initial assessment of the LCR samples indicated no biologically meaningful differences between Boulders, Coyote and Salt reaches, but sample sizes were low. An initial and provisional assessment of Chute Falls reach showed a significantly higher *Fst* value (increased homozygosity compared to other LCR reaches) which would suggest genetic variation between these groups. The source of this difference, however, is uncertain. It is possible that the difference was due to sample error (sample size 40), or it may have indicated breeding by a small number of adults above Chute Falls being reflected in increased homozygosity of the offspring (F1) generation. In any case, funding for analyzing the LCR tissue samples has never been procured, and further investigation into such anomalies would appear warranted. Although baseline genetics data for humpback chub in the LCR and other mainstem aggregations has been collected, the authors of these studies stated unequivocally that sample sizes were low and results should be interpreted cautiously (Douglas and Douglas, 2007; 2010; Connie-Keeler Foster and Wade Wilson, pers. com.).

Douglas and Douglas (2007) addressed the genetics of mainstem Colorado River humpback chub aggregations in Grand Canyon, and many of the results from their report were published in Douglas and Douglas (2010). Based on a sample size of 234 fish collected from nine areas in

Marble and Grand Canyons, Douglas and Douglas (2010) indicated that humpback chub downstream from the LCR were clearly connected by gene flow, and proposed downstream drift of larvae and juveniles as the scenario, with the LCR population being the primary source. However, contribution from occasional local reproduction by mainstem aggregations could not be excluded. Based on excess homozygosity, Douglas and Douglas (2010) specifically stated local reproduction may be occasionally occurring at Middle Granite Gorge. To date, this is the only baseline genetics data that researchers have concerning mainstem aggregations of humpback chub in Grand Canyon. The sample sizes obtained by Douglas and Douglas (2007; 2010) were generally very small, ranging from 4-26 fish from all aggregations except the LCR (n = 77) and Middle Granite Gorge (n = 80). This led Douglas and Douglas (2010) to suggest cautionary interpretation of some of their results, and underscores the need for additional baseline data.

Fin clips from approximately 300 humpback chub will be collected annually for DNA extraction and genotyping. Samples will be collected throughout the LCR as well as from translocated fish and from fish in each of the established mainstem aggregations. It is expected that establishing baseline data will take 2–3 years after which only periodic sampling (once every 3–5 years) would be required.

D.2 Personnel and Collaborations

The USGS lead for Project 8 is David Ward, a fishery biologist with GCMRC with expertise in native non-native fish interactions. Dr. Michael Yard is a fishery biologist with GCMRC with extensive experience in non-native fish removal projects. Brian Healy, Clay Nelson, and Emily Omana are fishery biologists with Grand Canyon National Park with extensive experience in non-native fish removal and native fish translocation projects who will provide expertise and guidance for the Trout Removal project (8.1) and the Chute Falls Translocation Project (8.2). Kirk Young, Dennis Stone, and David R. VanHaverbeke are fishery biologists with the U.S. Fish and Wildlife Service and will provide data, analysis and reporting on the Chute Falls Translocation project (8.2). Kirk Young has extensive fisheries management experience and will lead the Little Colorado River Invasive Aquatic Species Surveillance project (8.4). Dr. Wade Wilson is a geneticist with the U.S. Fish and Wildlife Service Southwest Native Aquatic Resources Research and Recovery Center and will expertise on the genetic monitoring of humpback chub (8.5). Dr. David Rogowski is a fisheries biologist with Arizona Game and Fish Department with expertise in aquatic ecology and conservation biology of fish and will provide research and management experience to the project elements in Project 8 including contributions to the Protocol Evaluation Panel review. Scott VanderKooi is the Deputy Chief and a supervisory biologist with GCMRC and will lead the Protocol Evaluation Panel review (Project 8.3).

D.3 Deliverables

Project elements will produce annual progress reports submitted to GCMRC and peer reviewed publications at project completions.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

Healy, B., C. Nelson, E. O. Smith, and A. Martin. Bright Angel Creek Trout Control Project. National park Service Trip Report. February 2013.

Nelson C., D. Ward, B. Healy, and E. O. Smith. Bright Angel Creek inflow trout reduction pilot study. Trip report submitted to GCMRC. February 2014.

Stone D. Summer 2013 monitoring and translocation of humpback chub (Gila cypha) above Lower Atomizer falls in the Little Colorado River, Arizona. Trip Report submitted to GCMRC. July 2013.

Spurgeon, J. J., C. P. Paukert, B. D. Healy, C. A. Kelley, D. P. Whiting. 2014. Can translocated native fishes retain their trophic niche when confronted with a resident invasive? Ecology of Freshwater Fish 2014: 1-11. Doi: 10.1111/eff.12160.

Whiting, D. P., C. P. Paukert, B. D. Healy, and J. J. Spurgeon. 2014. Macroinvertebrate prey availability and food web dynamics of nonnative trout in a Colorado River tributary, Grand Canyon. Freshwater Science, Published online May 7, 2014 (in press).

Pine, W. E., III, B. Healy, E. Omana Smith, M. Trammell, D. Speas, R. Valdez, M. Yard, C. Walters, R. Ahrens, R. Van Haverbeke, D. Stone, W. Wilson. 2013. An individual-based model for population viability analysis of humpback chub in Grand Canyon. North American Journal of Fisheries Management 33:626-641.

E.2. Publications in progress

Stone D., D. Van Haverbeke, M. Pillow, J. Walters, M. Cantrell, and K. Young. Translocation of Endangered Humpback Chub above Chute Falls in the Little Colorado River, Arizona. *In prep . North American Journal of Fisheries Management*.

Ward, D.L. and others. *In review.* A laboratory evaluation of tagging related mortality and tag loss in juvenile humpback chub, Gila cypha. *In Review*. *North American Journal of Fisheries Management.*

Ward, D.L. and R. Morton-Starner. *In prep*. Effects of water temperature and fish size on predation vulnerability of humpback chub to rainbow and brown trout.

E.3. Presentations at GCDAMP meetings

Morton-Starner, R. and D.L. Ward. 2014. An experimental evaluation of competition between rainbow trout and humpback chub. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER.

Ward, D.L. and R. Morton-Starner. 2014. Effects of water temperature and fish size on predation vulnerability of humpback chub to rainbow and brown trout. Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER – TWG and AMWG meetings.

E.4. Presentations at professional meetings

Morton-Starner, R. and D. L. Ward 2014. An experimental evaluation of competition between rainbow trout and humpback chub. Desert Fishes Council – Flagstaff, AZ.

Stone D. M. Translocation of Humpback Chub above Chute Falls in the Little Colorado River, Arizona. The 47th Joint Annual Meeting of the Arizona/New Mexico Chapter of the American Fisheries Society, Hon-Dah Resort and Casino, Pinetop, Arizona. February 2014.

Ward, D. L. and R. Morton-Starner. Effects of water temperature and turbidity on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout. Desert Fishes Council – Flagstaff, AZ.

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Arizona Department of Water Resources, 1990, Hydrographic survey report for the Silver Creek watershed, vol. I--general assessment, filed with the court November 30, 1990.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$53,700**	**$0**	**$7,500**	**$37,600**	**$68,200**	**$0**	**$17,500**	**$184,500**
				X			8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$49,700	$0	$2,800	$30,400	$0	$0	$13,000	$95,900
X							8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,000	$0	$4,700	$7,200	$68,200	$0	$4,500	$88,600
					X		8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$0	$0	$0	$0
X							8.4	Invasive Species Surveillance and Response	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0
				X			8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$0	$0	$0	$0	$0	$0	$0	$0
FY16																	
							8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$61,400**	**$0**	**$5,100**	**$45,300**	**$88,200**	**$0**	**$26,500**	**$226,500**
				X			8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$57,300	$0	$2,800	$37,500	$0	$0	$20,800	$118,400
X							8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,100	$0	$2,300	$7,800	$68,200	$0	$5,100	$87,500
					X		8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$20,000	$0	$600	$20,600
X							8.4	Invasive Species Surveillance and Response	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0
				X			8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$0	$0	$0	$0	$0	$0	$0	$0

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
							8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$69,400**	**$0**	**$6,300**	**$44,900**	**$138,200**	**$0**	**$37,300**	**$296,100**
				X			8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$56,200	$0	$2,800	$37,700	$0	$0	$26,500	$123,200
X							8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,400	$0	$2,300	$7,200	$68,200	$0	$5,900	$88,000
					X		8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$0	$0	$0	$0
X							8.4	Invasive Species Surveillance and Response	Young et al.	$4,400	$0	$0	$0	$45,000	$0	$2,600	$52,000
				X			8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$4,400	$0	$1,200	$0	$25,000	$0	$2,300	$32,900

Project 9. Understanding the Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons

Initial Estimate: FY15: $924,700; FY16: $946,200; FY17: $602,100

GCDAMP Funding: FY15: $924,700; FY16: $880,000; FY17: $572,000

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B. Project Summary

Over the past few decades, electrofishing and creel monitoring data collected by Arizona Game and Fish Department (AGFD) in Glen Canyon and Lees Ferry has shown that the rainbow trout (*Oncorhynchus mykiss*) fishery is characterized by three undesirable properties, including: (1) instability in population size that has led to decadal cycles of high and low fish abundance; (2) increased potential for negative interactions between rainbow trout and native fishes, especially the endangered humpback chub (*Gila cypha*), primarily due to rainbow trout population expansion downstream (Yard and others, 2011); and (3) an absence of the large rainbow trout that are highly valued by the angling community (Schmidt and others, 1998). Accordingly, much of the recent biological research conducted in Glen and Marble Canyons has focused on understanding factors that influence the size and health of the rainbow trout fishery (Korman and Campana, 2009; Anderson and others, 2012; Cross and others, 2013), as well as determining how Glen Canyon Dam operations and other factors may influence interactions between non-native trout and native species downriver (Yard and others, 2011; Korman and others, 2012; Melis and others, 2012).

These undesirable properties have also been a key concern to decision makers involved with the development of the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement. Fisheries modelling conducted to support the LTEMP process has identified a number of factors that lead to uncertainty in our ability to predict rainbow trout responses to flow management. Uncertainties identified prior to modelling as "critical" included the degree to which the seasonal timing of high flow experiments (HFEs) versus other factors contributes to variation in the strength of the trout recruitment response, and the degree to which experimental trout management flows (TMFs), if implemented, could limit rainbow trout recruitment in Glen Canyon (as well as other chub related uncertainties – see Project 7). The modelling also included other uncertainties, including the uncertainty in recruitment-flow relationships, rates of rainbow trout outmigration from Glen Canyon, and the degree to which larger rainbow trout populations in Lees Ferry limit trout growth. Modelling revealed that these other uncertainties had a large impact on variation in predictions, a similar effect to the "critical" uncertainties, and generally larger uncertainty in hydrologic traces over the next 20 years. Resolving uncertainty in the "critical" uncertainties as well as the recruitment-flow relationships will require the continuation of sampling focused on juvenile rainbow trout recruitment (i.e., RTELLS) alongside a well-designed plan for testing different flow management strategies (assuming that refining these uncertainties is necessary for management). Uncertainties in our ability to predict outmigration rates and growth, on the other hand, requires a combination of mark-recapture techniques which provide more precise estimates of movement and survival parameters, and process levels studies to better understand how movement and growth might respond to future conditions.

The Natal Origins Project (see Project Element H.2 in the GCMRC FY13–14 workplan) was designed to address the need for mark-recapture studies to better understand rainbow trout population dynamics, especially movement. Previous modelling work using just catch data found it difficult to parse out whether local reproduction in Marble Canyon contributed meaningfully to populations or whether population dynamics were driven primarily by outmigration from the Lees Ferry reach (Korman and others, 2012). Preliminary results from the Natal Origins study suggest that movement is lower than expected, however, it is unclear whether movement rates may vary over time either as fish age or in response to changing environmental conditions. Furthermore, it is unclear how well these drift-feeding fish can maintain locally self-sufficient populations in Marble Canyon where environmental factors (i.e., reduced underwater light due to intermittent periods of high turbidity) may influence their ability to effectively forage (Kennedy, unpublished data). Another unknown is why local reproduction does not occur in Marble Canyon more than it does in Glen Canyon (Korman and others, 2012; also see Project 10). Physiologically, fish that exhibit reduced foraging capacity because of low light conditions and/or prey size and availability will often not be able to successfully spawn since gamete development is energetically costly (Hutchings, 1994; Hutchings and others, 1999). For the FY15–17 workplan, we developed a suite of research and monitoring projects that will elucidate some of the mechanisms behind changes in trout abundance, survival, movement, reproduction, and growth in Glen and Marble Canyons. These research efforts will provide information that can be used to better understand the potential for negative interactions between non-native trout and native species like humpback chub, and perhaps identify experimental treatment options for mitigating high rainbow trout abundance downstream of Lees Ferry.

Since the early 1990's the Arizona Game and Fish Department (AGFD) has monitored the Lees Ferry rainbow trout fishery via electrofishing in multiple seasons, providing data that has fostered the development of research projects to investigate causal mechanisms behind changes in population and trout size over time. These data have been used to develop catch per unit effort (CPUE) indices as a surrogate for population size, but other research and monitoring programs have commenced that estimate population size via more robust mark-recapture methods. To reduce redundancy between programs and optimize the utility of data generated (e.g., mark-recapture population estimates in lieu of CPUE), a transition is needed from current research and monitoring efforts to a longer-term monitoring program that maintains a robust multi-pass mark-recapture effort necessary to generate reliable estimates of vital rates for rainbow trout in Glen and Marble Canyons. We propose to develop and implement a plan for this transition during FY2015-17. Monitoring of juvenile trout will also continue under the Rainbow Trout Early Life Stage Survey (RTELSS) project (Project Element 6.7), while creel data from the Lees Ferry fishery will continue to be collected by AGFD (Project Element 6.8). Collectively, these monitoring data are essential to the management of the Lees Ferry trout fishery because they provide an indication of the influence of Glen Canyon Dam operations and other naturally occurring disturbances in the Colorado River ecosystem (CRe) on the health of the rainbow trout fishery.

In addition to monitoring adult and juvenile rainbow trout populations, a suite of new research activities will improve our understanding of the mechanisms that drive rainbow trout population dynamics as they relate to dam operations and flow management actions. Specifically, these research projects will target questions related to characteristics of the physical habitat (e.g., channel-bed texture, water temperature, turbidity, water depth, and flow) and food base that may limit trout growth, size, and reproduction including: (a) a quantification of the energy (lipid) reserves of drift-feeding trout in Glen and Marble Canyons to examine potential drivers of trout growth, movement, survival, and reproduction under varying light intensities pre- and post-monsoon; (b) a morphometric analysis of feeding structures in drift feeding fish to assess whether feeding efficiency is constrained by the size of invertebrate prey in the CRe; (c) a meta-analysis of data on the effects of light intensity, prey size, predator size, and turbidity on visual reactive distances of drift feeding fish, which will be used to develop an encounter rate model that predicts how light intensity and prey size affects trout foraging success and growth in Glen and Marble Canyons; (d) a laboratory study to assess the feasibility of using dam operations following fine sediment inputs (sub-sand sized) into Marble Canyon so as to assess whether or not managing turbidity is feasible as a trout management tool during minimum-volume dam release years; (e) development of bioenergetics models to quantify the effects of turbidity and food availability on trout growth in Marble Canyon; (f) an assessment of the mechanisms that limit trout growth in other tailwaters using data collected during the tailwater synthesis project; (g) development of population dynamic models that assess growth, reproduction and movement of rainbow trout between Glen and Marble Canyons; and (h) an evaluation of the effects of fall High Flow Experiments (HFE) on the growth, survival, movement, and condition of young-of-the-year rainbow trout via comparison of data from HFE and non-HFE sampling years. Collectively, results from these monitoring and research projects will be used to identify key drivers behind changes in rainbow trout population size, movement, survival, reproduction, size, and condition that will be used to better manage the trout fishery while protecting endangered fish populations in the CRe.

C. Background

Rainbow trout data collected in both Lees Ferry and Marble Canyon over the last few decades has been synthesized recently to provide a more holistic picture of rainbow trout population dynamics that points to uncertainties in our understanding and ultimately in our ability to predict the effects of management options. Korman and others, (2012) quantified the connections between certain flow characteristics and rainbow trout recruitment and attempted to estimate movement from Lees Ferry and Marble Canyon. This exercise illustrated that the sort of data collected over the preceding decades (mainly CPUE), while useful, was not capable of answering important questions about the origins of rainbow trout in Marble Canyon. More recent modelling to support the LTEMP process has reiterated this uncertainty, while also suggesting that our understanding of relationships between flows and rainbow trout recruitment require more precision to manage both rainbow trout and humpback chub. In short, if conditions favorable to high abundance of trout were desired, then operations that included steady summer flows with frequent equalization and HFE events would be implemented and rainbow trout monitoring efforts could be minimal. Similarly, if conditions favorable to humpback chub were favored, sufficient evidence exists to suggest that the opposite conditions (as few HFEs and equalizations as possible and unsteady summer flows) would be recommended. Under this scenario, again little rainbow trout monitoring would be required. However, to manage for intermediate conditions requires continued research and monitoring of rainbow trout recruitment, movement, growth and abundance.

During FY13–14, studies of rainbow trout were partitioned in such a way that research into the abundance and movement of rainbow trout below Lees Ferry was separated from research into the growth and abundance of these fish in Glen Canyon. For FY15–17, we have integrated much of this work into Project 9. Findings from these research activities in 2013–14, though preliminary (GCMRC Annual Reporting Meeting, January 2014; http://www.usbr.gov/uc/rm/amp/twg/mtgs/14jan30/), suggest that the rainbow trout population in Glen and Marble Canyons is characterized by instability in population size, uneven spatial distribution, seasonally and spatially variable growth rates, and higher than expected survival upstream of the LCR. Furthermore, there is growing evidence linking rainbow trout abundance to declines in juvenile humpback chub survival near the LCR confluence (obtained through mark-recapture efforts begun during NSE and continued as part of the Natal Origins and Juvenile Chub Monitoring projects; Yackulic, unpublished data). To date, only limited downstream movement of tagged rainbow trout has been detected, however, many rainbow trout near the LCR are likely immigrants from Glen Canyon. Thus, despite the extremely high densities of rainbow trout in upper Marble Canyon, only a small proportion has moved downstream. Although small relative to upstream abundance, these numbers of rainbow trout appear to have been sufficient to significantly reduce juvenile humpback chub survival near the LCR confluence. At the same time, these results are based on only a few years' data and movement appears to be lower than measured during the mechanical removal period from 2003–06 (the only other period when mark-recapture techniques were used and thus allows for inferences to be made about movement). This suggests that movement likely varies through time and that the number of rainbow trout in lower Marble Canyon may correspond directly to increases or decreases in emigration rates or recruitment rates in Glen Canyon or Marble Canyon

The ability to predict movement of rainbow trout might improve if a better understanding were developed as to why they were moving more in the early 2000s than they are now. Turbidity, changes in the prey base and the increasing energetic needs of older rainbow trout have all been suggested as potential factors that could explain these differences. Previous and ongoing bioenergetic modelling (McKinney and Speas 2001; Dodrill, unpublished data), as well as a lipid pilot study, and measurement of weight losses and gains suggest that the limited quality and quantity of drift in Glen Canyon and Marble Canyon may limit growth to a few months of the year. As rainbow trout grow, they appear to spend many months of the year only meeting maintenance energy requirements, but not growing. This could be due to a number of causes including seasonal increases in turbidity that negatively affect rainbow trout foraging ability, limited food resources, intense competition due to high fish densities, or other factors. The low rates of downstream movement by rainbow trout in recent years may be related to relatively low turbidity levels and most fish being small, thus more likely to find adequate food. In the future, movement may increase to levels seen during the mechanical removal study as fish grow and require more food, if turbidity increases, or if other conditions that influence fish movement rates change. We believe this warrants the continuation of more directed studies along this research line, with greater emphasis on measuring the short-term physiological effects of dam operations on trout populations and modeling the interacting mechanisms that potentially control trout growth, population size, distribution, and recruitment in Glen and Marble Canyons.

Rainbow trout were initially introduced to Grand Canyon (circa, 1920–30's) through stocking in small tributaries, which then resumed once flow regulation commenced with completion of Glen Canyon Dam in 1964 (refer to unpublished stocking reports: Stricklin 1950; AGFD records). During the "stocking era," the rainbow trout fishery was sustained by annual stocking at Lees Ferry (1964–1997) with minimal recruitment from natural reproduction (Maddux and others, 1987; McKinney and others, 2001). Rainbow trout were widely distributed throughout the Colorado River in advance of the most fish surveys (Carothers and others, 1981; Maddux and others, 1987) and occurred in areas used by native fish (Kaeding and Zimmerman, 1983; Valdez and Ryle, 1995). The extent of interactions between native and non-native fish during this period is not well understood, and is often presumed to have been limited in comparison to more recent years (Valdez and Ryel, 1995; Marsh and Douglas, 1997).

Since 1991, the fishery has been increasingly sustained by natural recruitment and stocking was completely phased out by 1998 (McKinney and others, 2001). While limited recruitment was occurring prior to 1991 (Maddux and others, 1987), this transition to a "recruitment era" is often attributed to implementation of modified low fluctuating flows (MLFF; USDOI, 1996; Walters and others, 2000). Demography of rainbow trout during the recruitment era is closely linked not only to implementation of MLFFs, higher-flow periods, such as High Flow Experiments (HFE; USDOI, 2011a) and equalization flows (Interim Guidelines; USDOI, 2007). Spring-timed high flow experiments in 1996, 2000, and 2008, while higher and steadier dam operations (response to spring runoff forecasts in the upper Colorado River basin) during the middle of the water year, either to mitigate the probability of spills from the dam or equalize water storage between Lakes Powell and Mead flows in winter to spring seasons, as in 1997, 2008 and 2011, led to recruitment of large numbers of juvenile rainbow trout in subsequent years (Korman and others, 2012; Korman and others, unpublished data). Research surrounding these flow events suggests that this recruitment, driven by increased juvenile survival and growth, was mainly attributable to increased food availability in the drift. In turn, this was linked to higher production of key drifting species of insects upon which rainbow trout rely heavily (blackflies and midges; Cross and others, 2013; Kennedy and others, 2013). Although increased local reproduction led to a self-sustaining population, the "recruitment era" for the rainbow trout fishery has been characterized by undesirable properties such as fluctuations in population size, a decline in trout size (Schmidt and others, 1998), and an increased potential for negative interactions with humpback chub (Yard and others, 2011).

On one hand, there is a renowned and highly valued sport fishery of rainbow trout whose population is self-sustaining. On the other hand, there is an endangered fish population separated from the trout fishery by distance, although not entirely insular from the other, and whose status appears negatively related to the population dynamics of rainbow trout found upstream (Yard and others, 2011; Yackulic, and others, in prep.). The intersection between these two important but, interacting fish populations appears strongly linked to causal mechanisms that control growth and population density, particularly for trout. Nonetheless, the degree to which dam operations and associated factors (i.e., population cycles) interact to affect rainbow trout movement and growth is considered one of the largest uncertainties associated with the Glen Canyon Adaptive Management Program (GCDAMP; McKinney and others, 2001; McKinney and Speas, 2001; Cross and others, 2011). This is the central motivation driving the proposed research and monitoring projects in FY15–17.

This uncertainty was highlighted during modelling for the recent LTEMP process. While there is a good understanding of the direction of flow impacts on trout recruitment (Korman and others, 2012) and an improving understanding of the magnitude of the effect of rainbow trout on juvenile humpback chub survival (Yackulic and others, in prep.), management options that could meaningfully decouple trout and sand resources from humpback chub are not being considered. Presumably, this is due to the costs of resolving these issues in terms of other resources. Whereas, the density of the stocked rainbow trout fishery present 20-30 years ago was relatively easy to manage by changing stocking strategies, changes in in flow management have led to a rainbow fishery that is more difficult to manage. More recently, HFEs and equalization flows appear to have led to increased rainbow trout recruitment. While some management options being considered (e.g., TMFs) could counteract increased recruitment linked to an increasing frequency of HFEs if applied selectively, trout abundance or recruitment are likely to continue to be instable. In other words, the problem of a naturally reproducing, and thus difficult to manage, rainbow trout fishery is unlikely to disappear given future dam operations being considered in proposed alternatives for the LTEMP EIS. Each alternative being considered would require maintaining a rainbow trout fishery and conserving sand resources while working to recover humpback chub, and the science to support this detailed tradeoff analysis is necessarily intense.

Recognizing this uncertainty has led to a plethora of hypotheses regarding the causal source(s) regulating rainbow trout density, recruitment, and growth. Cause and effect relationships are more easily determined when a single factor is chronically apparent and measureable; all the same, the difficulty in discerning causal mechanisms often arises because: (1) an effect is acutely strong but short lived; (2) a mechanism is no longer present but the antecedent effect remains; and (3) multiple causal factors may be involved. Since growth is an integrated measure across time, the use and application of different metrics that exemplify growth over different time scales (long-term vs. short-term) are helpful in discriminating between effects from different environmental factors. Monitoring programs are important for documenting population characteristics (e.g., abundance, size distribution, and occurrence; Project Element F in the GCMRC FY13–14 Workplan), but are not a very effective approach in time or cost for determining causation, particularly when used as the sole method. How then do we better understand what factor(s) might be regulating trout growth?

Although rainbow trout are one of the most abundant fish species in the CRe, trout densities and growth rates decline substantially with distance downstream from Glen Canyon Dam (Makinster and others, 2011; Korman and others, unpublished data). Spatial and temporal variation in the invertebrate prey base and how it is consumed by fish may play an important role in determining individual fish growth, and subsequently, fish survival, movement and reproduction throughout the CRe. Non-native rainbow trout and brown trout (*Salmo trutta*) are likely to compete with (and prey on) native fish (Donner, 2011), including humpback chub (Yard and others, 2011), because the foraging mode used by all three fish species relies predominately on drifting invertebrates (Cross and others, 2013). Larger invertebrates are often more vulnerable and therefore preferentially selected by fish predators over small prey because ease of detection and retention while foraging, particularly since prey size is also correlated with energy content (Breck and Gitter, 1983; McKinney and others, 2001). Although food is often one of the most commonly limiting resources in aquatic ecosystems, visual sight feeders like rainbow and brown trout may have encounter rates that are periodically reduced; in essence the number of invertebrates a fish encounters daily, thereby affecting growth rates. Consequently, understanding these biotic interactions is of significant concern to the management of the CRe (Yackulic and others, 2014).

Owing to a recent and extensive tagging effort associated with the Natal Origins of Rainbow Trout research project (see Project Element F.4 in the GCMRC FY13–14 workplan) we are now able to estimate size-based seasonal growth rates for rainbow trout using across-trip recapture data, as well as model length-at-age growth trajectories for trout in downstream reaches (i.e., from Glen Canyon to the Little Colorado River (LCR) confluence) using a von Bertalanffy growth curve. Other data are being collected in conjunction with the Natal Origins project, including integrated drift samples, trout diet (rainbow and brown trout), trout lipid mass, and gill branchial arches, as well as physical data (turbidity and temperature). In particular, lipid analysis will provide a sensitive indicator of the physiological condition of trout since fat stores in fish become depleted during prolonged starvation events (Adams, 1999; Parrish, 1999). This analytical tool will be very effective in evaluating the effects of food availability and fish density and size on the energy storage capacity of trout residing in different reaches of the Colorado River, which will elucidate potential mechanisms behind between-reach differences in reproductive capacity (Adams, 1999; Cleary and others, 2012). Preliminary findings from the above research projects indicate seasonal differences in trout growth that are likely due to a combination of factors, including drifting prey availability (food resource limitations; Kennedy, unpublished data), trout densities (intra-specific competition; Korman and others, unpublished data), turbidity events (prey detection), and energy storage (feeding efficiencies; Dibble, unpublished data). The metrics from these and future data collections will be extremely useful for comparing empirical findings to the outcomes from predictive models (encounter rate and bioenergetics models).

Data collected in FY13–14 has provided significant insights on rainbow trout population dynamics in the CRe as well as in other regulated rivers across the West. Management concerns for the trout fishery in the CRe downriver of Glen Canyon Dam are similar to those in other systems, including a decline in trout size and catch, potential interactions with endangered species, whirling disease, seasonal low flow conditions, diminished food base, parasites, and other natural and anthropogenic factors that influence trout growth and survival. Analysis of tailwater data has revealed that a decline in the size of rainbow and brown trout in other tailwaters is primarily correlated with dam operations (hydropeaking and seasonal and annual flow volume) and high densities of small and medium-sized rainbow and brown trout. Additional analyses planned in FY15–16 (see Project Element 9.8) will elucidate some of the mechanisms behind changes in trout size and growth in other tailwaters, which will not only inform the management of Glen Canyon Dam but will inform the management of a broader number of tailwater systems in the Western U.S.

To resolve uncertainties associated with factors that regulate trout growth in Glen and Marble Canyons and in other tailwater systems, we propose complementing long-term rainbow trout monitoring with a suite of new research activities.

C.1. Scientific Background

As specified in the FY13–14 Work Plan, many of the same hypotheses thought to explain the mechanisms of rainbow trout growth still pertain to this project. For brevity we have reduced some of the original text, but have included some additional research hypotheses that support the proposed project elements.

Hypothesis 1 **(H1)** *The strain of rainbow trout present in Glen Canyon is incapable of growing to large sizes (i.e., >20 inches).* This hypothesis attributes diminished rainbow trout growth to changes in the genetic strains historically stocked at Lees Ferry, and does not consider physiological conditions for trout growth as affected by dam operations (see GCMRC FY13–14 Workplan, Project Element H.1).

Hypothesis 2 **(H2)** *The current prey base, composed chiefly of midges and black flies, can support the growth of smaller rainbow trout, but does not provide enough energy to allow for growth in large rainbow trout.* **H2** argues that there have been shifts in the foodbase that now leave it incapable of supporting larger rainbow trout. While dam operations can shift the foodbase to favor the recruitment and growth of small rainbow trout (Cross and others, 2011), growth and survival of large rainbow trout appears largely unaffected by Glen Canyon dam operations. Possible causes of this shift in the foodbase include declining nutrient inputs from Lake Powell as the reservoir has aged (Stockner and others, 2000*; see GCMRC FY15–17 Workplan,* Project Element 5.3. [nutrient budget]), introduction of invasive species (i.e., New Zealand mudsnail (*Potamopyrgus antipodarum*); Cross and others, 2010), and changes in channel-bed texture as the Glen Canyon reach was winnowed of finer sediment initially in summer 1965 and then during other periods of higher dam releases over time (Grams and others, 2007). Changes in invertebrate composition could lead to changes in both the seasonal availability of drifting invertebrates (there is currently ~100-fold variation in drift rates among seasons; Kennedy, unpublished data) and in the prevalence of high quality drift (i.e., large prey items such as *Gammarus*), both of which might strongly constrain growth of large rainbow trout while still allowing small rainbow trout to thrive. Support for this hypothesis comes from McKinney and Speas (2001), who observed size-related asymmetries in rainbow trout diet and energy intake that suggests larger sized trout are food-limited more often than smaller fish. Although the total amount of prey available to support rainbow trout populations may have increased during this time period (Angradi and Kubly, 1993; Blinn and others, 1995; Benenati and others, 1998), juvenile trout appear to be the primary beneficiaries of any such change (McKinney and Speas, 2001). More recent research on the Glen Canyon food web (Cross and others, 2011) supports these observations.

A corollary to **H2** is that some combination of rainbow trout dispersal patterns, food availability, and declining prey detectability explains the declining abundances of rainbow trout at distances further downstream from Lees Ferry (Carothers and Brown, 1991; Makinster and others, 2011). Turbidity increases downriver (Voichick), and since rainbow trout are visual feeders, it is more challenging for them to see food. However, the importance of this effect relative to declining food availability and dispersal rates is unknown (Barrett and others, 1992; Stuart-Smith and others, 2004).

Defined below, are a set of secondary hypotheses where we explore some of the mechanisms underlying ***H2***; these hypotheses are not mutually exclusive. Under

Hypothesis 2.1 (**H2.1**), *Feeding morphology differs among rainbow trout, brown trout, and humpback chub which leads to resource partitioning among drift feeding fish*. We expect that morphological differences in the branchial-arch/gill-raker feeding structure exists among the three drift feeding species, which leads to a preferential consumption of different prey sizes. If true, differences in feeding efficiencies due to feeding morphology rather than behavior may explain the differential consumption of prey observed between trout species (Yard, unpublished data). The anatomical similarities and differences found in feeding morphology among these three fish species may partially explain why rainbow trout and humpback chub have a high diet overlap and a potential for competitive interactions (Donner, 2011), whereas brown trout diet consists primarily of large prey items, with a strong preferential use of *Gammarus* and juvenile fish (Yard and others, 2011).

Under ***Hypothesis 2.2*** (**H2.2**), *Feeding morphology changes with fish size and leads to feeding inefficiencies*. This hypothesis presupposes that feeding efficiencies change as a fish grows which should lead to a selection of specific prey based on size, a trend that favors consumption of larger invertebrates (chironomids → simuliids → gammarids) as a fish grows (MacNeill and Brandt, 1990). Because anatomical features often change in size and shape disproportionately as a fish increases in length (increase in gill-raker spacing as a consequence of growth), it is likely that these morphological differences should reduce the retention efficiencies for smaller prey items with increasing fish length. Therefore, we would expect to observe increases in the mean prey size as a fish becomes larger, along with a commensurate decrease in the variation of the prey size distributions found in the diet. Under environmental conditions where *prey availability is not limited*, we should expect that the diet of small fish will be more similar to the invertebrate size distributions in the drift, whereas the diet for large fish should contain a higher proportion of larger invertebrates than the actual size distributions available in the drift (high electivity indices). In contrast, under environmental conditions when *prey availability is limited*, we should expect reduced feeding efficiencies for larger sized fish, such that the quantity of food items found in the diet, scaled according to fish size, will be less in larger fish than in smaller fish. Thus, limited prey diversity (**H.2.0**) favoring small sized dipterans impose growth restrictions on larger sized trout due to feeding inefficiencies.

Nevertheless, it is also possible that feeding efficiencies of trout are not limited by feeding morphology, but by other mechanisms such as visual prey detection. Under

Hypothesis 2.3 (**H2.3**); *Feeding efficiencies of trout are limited by visual acuity,* presupposes that varying underwater light intensities (Hansen and others, 2013) mediated by turbidity and prey size (Barrett and others, 1992) affect reactive distances of visual sight feeders, particularly in rainbow trout. This is one of the most abundant fish species in the CRe; even so, it has been observed that trout densities and growth rates decline with increasing turbidity levels as found downstream (Korman, unpublished data). Under increased turbidity conditions we expect that the quantity of dietary items found in small and large fish will be reduced regardless of prey availability in the drift (Hansen and others, 2013).

Hypothesis 3 **(H3)** *The growth of large rainbow trout is limited by exploitative competition for limited prey items*. The diet composition of large and small rainbow trout overlap (i.e., their production is primarily supported by midges, black flies, and *Gammarus*; McKinney and Speas, 2001; Cross and others, 2011); however, smaller rainbow trout may be able to subsist on smaller prey items, and this may in turn affect food availability for larger rainbow trout. Many of the smaller prey items (small *Gammarus* and 1st instar larvae of midges and black flies) consumed by small rainbow trout represent early life stages of species that large fish would be better able to exploit if these prey items continued to mature. Since recruitment of smaller rainbow trout is tied to dam operations, **H3** posits an indirect and time lagged linkage to dam operations. While **H2** and **H1** predict no changes in large rainbow trout growth if small rainbow trout numbers are suppressed, **H3** predicts an increase in the growth of large rainbow trout if small rainbow trout are suppressed. **H3** can also be extended to argue that while HFEs augment juvenile recruitment, the dynamics in the following years may be chiefly driven by intraspecific interactions between younger and older age-classes of trout, as opposed to physical factors (Schlosser 1985; Walters and Post, 1993).

Hypotheses 4 **(H4)** *Operational constraints that occurred in 1990 limit the growth of large rainbow trout.* **H4** directly links the lack of large rainbow trout to changes in dam operations. **H4** posits that the load-following dam operations that occurred during the stocking era created habitat that was more beneficial to large rainbow trout by favoring a fast-growing and high-quality early successional algal assemblage, creating daily surges in invertebrate drift (Perry and Perry, 1986). This also favored larger invertebrate prey items, all of which sustained the growth of larger rainbow trout (Barrett and others, 1992; Graf, 1995; Stuart-Smith and others, 2004). Growth studies on young-of-year rainbow trout have demonstrated that daily flow variation has significant effects on growth for early life stages (Korman and Campana, 2009). However, we lack a similar understanding of how daily variation in discharge affects growth of larger rainbow trout.

Hypotheses 5 **(H5)** *Depressed growth rates leads to rainbow trout movement.* Predator-prey dynamics may occur under conditions where invertebrate prey are initially plentiful (e.g., spring-floods or equalization flows stimulate invertebrate production); conditions favoring increased growth and physiological condition may lead to successful trout reproduction and recruitment (Korman and others, 2011). Subsequently, high trout densities the following year may exceed the carrying capacity of the food resources and outstrip the food supply (**H2**). Under this scenario, **H5** predicts that fish are more likely to move when metabolic requirements are not met, due to either an increase in foraging time when invertebrate prey are less available (**H2**, resource limitations), or when there are strong competitive interactions occurring within or between different sized cohorts (**H3**, intraspecific competition). If movement is governed by predator-prey dynamics, downstream dispersal may occur episodically due to resource depletion (**H2**) or gradually over time depending on the relationship between trout densities and resource availability (**H3**).

The motivation for these proposed research projects is to better understand how growth affects rainbow trout dynamics so as to improve the recreational fishing experience for rainbow trout at Lees Ferry, while at the same time protecting and maintaining native fish populations downstream in Marble and Grand Canyons. Being able to distinguish among these multiple hypotheses will help inform the types of experiments the GCDAMP might evaluate during the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) to meet goals for native and non-native fishes. If the research outlined below supports either **H1** or **H2.0-2.3**, then experimental changes in dam operations alone are unlikely to provide the conditions necessary to support the large rainbow trout that are sought by anglers. If we find support for **H1**, then this would suggest that the GCDAMP might pursue experimental stocking of alternative strains of rainbow trout, which are capable of growing to large size, into Glen Canyon. If the proposed research primarily supports **H2.0-2.3**, then the GCDAMP could consider experimentally introducing invertebrate species from other Colorado River Basin tailwaters (i.e., San Juan, Flaming Gorge, etc.), particularly larger taxa, and/or consider habitat modification (e.g., flows, large woody debris additions, or a temperature control device). If the proposed research primarily supports **H3** or **H4**, then the GCDAMP might consider alterations in dam operations. In recent years, dam operations designed to achieve goals for sediment and native fish (i.e., HFEs and Low Steady Summer Flows) or meet equalization requirements (i.e., 2008 and 2011-12), have created pulses of rainbow trout recruitment (Korman and others, 2012). As a consequence, recreational catch rates in Glen Canyon have increased following these operations, yet the large rainbow trout that are sought by many anglers are absent. Further, these pulses of recruitment and subsequent downstream dispersal (**H5**) have led to costly and controversial rainbow trout removal efforts designed to reduce the threat that they pose to endangered humpback chub (Coggins and others, 2011). One specific management option available to the GCDAMP is moving towards dam operations that will suppress juvenile recruitment. Suppressing juvenile rainbow trout recruitment might improve growth of larger rainbow trout either by lowering the degree of competition with smaller size classes (**H3**) or by creating more ideal habitat conditions (**H4**).

C. 2. Key Monitoring and Research Questions Addressed in this Project

This project directly addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) previously identified by the GCDAMP. In addition, Project Elements 9.9 and 9.10 in the current workplan comply with directives from the Secretary of the Interior to ensure effective and coordinated implementation of Environmental Assessments associated with the High Flow Experimental releases and with Non-Native Fish Control downriver of Glen Canyon Dam.

Primary SSQ addressed:

- SSQ 1-5. What are the important pathways, and the rate of flux among them, that link lower trophic levels with fish and how will they link to dam operations?
- SSQ 1-6. Are trends in the abundance of fish populations, or indicators from fish such as growth, condition, and body composition (e.g., lipids), correlated with patterns in invertebrate flux?
- SSQ 3-5. How is invertebrate flux affected by water quality (for example, temperature, nutrient concentrations, turbidity) and dam operations?
- SSQ 3-6. What GCD operations (ramping rates, daily flow range, etc.) maximize trout fishing opportunities and catchability?
- SSQ 5-2. Is invertebrate flux affected by water quality (e.g., temperature, nutrient concentrations, turbidity) and dam operations?

- SSQ 5-6. Do the potential benefits of improved rearing habitat (warmer, more stable, more backwater and vegetated shorelines, more food) outweigh negative impacts due to increases in non-native fish abundance?

Primary Core Monitoring Information Needs addressed:
- CMIN 1.5.1. Determine and track the composition and biomass of drift in the Colorado River in conjunction with measurements of flow, nutrients, water temperature, and light regime.

Research Information Needs addressed:
- RIN 1.1. What are the fundamental trophic interactions in the aquatic ecosystem?
- SIN 7.2.2. Which water quality variables influence food base and fisheries in the CRE?
- IN 6.3. How is the abundance of vertebrate consumers affected by seasonal shifts in food base abundance in the CRE?
- RIN 1.4.3. How do top-down effects (grazing and predation) affect the abundance and composition of benthic invertebrates?

D. Proposed Work- Monitoring and Research Projects

D.1. Project Elements- Research

Project Element 9.1. Rainbow Trout Population Dynamics – Ongoing Modelling and Future Monitoring

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William Persons, Fishery Biologist, USGS, GCMRC
David Rogowski, Fishery Biologist, AGFD
Michael Yard, Fishery Biologist, USGS, GCMRC
Scott VanderKooi, Supervisory Biologist, USGS, GCMRC
Luke Avery, Fishery Biologist, USGS, GCMRC

The Lees Ferry rainbow trout fishery is one of the most intensively studied tailwaters in the western United States (Dibble pers. comm.). Standard monitoring in most tailwaters consists of CPUE indices based on a single sampling trip (typically in the fall), whereas monitoring in Glen Canyon has traditionally consisted of three seasonal trips to collect CPUE data. Given the sensitivity of the fishery to dam operations and the interests of stakeholders, extra effort is perhaps warranted, however, much of the concern regarding rainbow trout revolves around fish not residing in the tailwater. Therefore, any monitoring design should consider questions regarding rainbow trout both in Glen and Marble Canyons. Downstream of Glen Canyon, monitoring has traditionally consisted of CPUE based indices based on 1-2 trips per year as part of the SWEF project (project element 6.4). Recent modelling efforts (Korman and others, 2011 and 2012; Yackulic, unpublished data) suggest that these data were not sufficient to address competing hypotheses concerning the origin of rainbow trout in Marble Canyon. Intuitively, this makes sense since the only indication of provenance in catch data comes from few tag recaptures of adult fish (Maddux and others, 1987) and differences in size structure at different locations (Korman and others, 2012), and these differences can be explained via multiple processes (e.g., different combinations of spatial variation in timing of spawning, growth, survival and movement). This suggests the need for mark-recapture studies, which allow for estimation of key process variables (survival, growth, movement, etc.) and was the motivation for the Natal Origins project. The increased information in mark-capture data over catch data is illustrated by the dramatic increases in our understanding of the roles of temperature and trout in the dynamics of juvenile humpback chub through NSE and then JCM sampling (see Project Element 7.2) combined with recent modelling for LTEMP process. For example, these data allowed us to determine that recent decreases in juvenile humpback chub survival in a mainstem reference reach (RM 63-64.5) in response to increasing rainbow trout numbers were somewhat offset by years of high juvenile production and outmigration from the LCR such that juvenile chub numbers initially increased even as survival decreased (Yackulic and others, 2014 annual reporting). The Natal Origins project has helped answer questions about how different process variables (survival, growth and movement) vary throughout Glen and Marble Canyons. It is likely, however, that rates of these variables fluctuate through time, warranting continuation of this research in some form at least for the duration of the HFE protocol (through 2020).

In light of the above, the goals of this project are two-fold. Firstly, to analyze ongoing Natal Origins research activities to better understand rainbow trout population dynamics in Glen and Marble Canyons and secondly, to use information gained to develop recommendations for future monitoring and research. An initial assessment informed by modelling for the LTEMP process and guidance from DOI leadership and stakeholders, suggests that some version of the Natal Origins project will be needed in the near future so long as the GCDAMP seeks to maintain naturally reproducing populations of rainbow trout and a healthy humpback chub population in the same river. While primarily focused on rainbow trout downstream of Lees Ferry, the Natal Origins project also includes sampling in Glen Canyon, particularly in the fall when large numbers of fish are marked with PIT tags. Ongoing analyses suggest that data from this effort can be analyzed to provide estimates of the actual abundance of rainbow trout in Glen Canyon with no additional sampling (Dzul, unpublished data). If correct, catch indices as well as actual estimates of the state variable of interest (i.e., abundance) will be able to be calculated from data collected during the marking efforts described above. While minor differences in sampling protocols exist between this work and those used to collect the long-term data set, a comparison is needed to determine if a mark-recapture approach can be used in lieu of the CPUE monitoring that has been in place since 2000. We propose that additional data be collected in 2015 and that all overlapping data be evaluated to determine the suitability of a Natal Origins-type approach to meet long-term status and trend information needs. AGFD will continue to be funded through FY2015 to monitor the Lees Ferry fishery; however, continuation of monitoring in outlying years (FY2016-2017) will be dependent on the analysis of monitoring protocols and recommendations from the PEP.

As with the Juvenile Chub Monitoring project (Project Element 7.2), the Natal Origin Research project (Project Element 9.2) is scheduled to be completed by the end of FY2016. This leaves a significant data gap in outlying years for information on rainbow trout abundance, distribution, and movement in Glen and Marble Canyons in response to dam operations and other management actions outlined in environmental assessments for HFEs and nonnative fish control (USDOI, 2011a and 2011b) and other management documents. To avoid this gap, a transition of the Natal Origin Research project from a research focus to a monitoring effort needs to occur. We propose that GCMRC and its cooperators collaboratively develop a plan for this transition and include it among the topics to be reviewed by the fisheries program protocol evaluation panel (PEP; see Project Element 8.3). The new monitoring project will begin in FY17 following review and implementation, as appropriate, of the PEP's recommendations by GCMRC.

Project Element 9.2. Detection of Rainbow Trout Movement from the Upper Reaches of the Colorado River below Glen Canyon Dam/Natal Origins

Josh Korman, Ecometric Research, Inc.
Michael Yard, Fishery Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The central objectives of this research project are to (1) determine the natal origins of rainbow trout in the Marble Canyon/LCR confluence area via a large-scale mark and recovery effort, (2) to evaluate the linkage between trout populations in the Lees Ferry reach and Marble Canyon, (3) assess the efficacy of the proposed alternative of a trout removal effort between the Paria River to Badger Rapid (PBR), (4) develop analytical methods for monitoring abundance, survival, recruitment and capture probability of rainbow trout in the CRe. And lastly (5) studying the response of juvenile native fish to changes in trout density near the LCR area resulting from removal and experimental flow treatments will be used to support the data and analytical requirements as per the Biological Opinion for Glen Canyon Dam operations including high flow experiments and nonnative fish control (USFWS 2011) (see project element 7.2 [Juvenile chub monitoring]).

This project as originally described in the FY11–2012 Work Plan (BIO 2.E18.11, 12), has been modified and expanded (see FY13–14 Work Plan) with fieldwork continuing through the end of FY16. The scheduled completion for this project is 1st quarter of FY17. This study is a research project to determine if Glen Canyon is the natal source of trout emigrating into the downstream reaches of Marble and Grand Canyons (Korman and others, 2011). Information from this project will help resolve some of the uncertainties about prescribing nonnative fish control activities such as fish suppression flows (e.g., LTEMP possible alternatives), or in locations that are geographically distant to the area of concern (Little Colorado River confluence area). This project is based on existing information (Coggins, 2008; Korman and others, 2012) that concludes that rainbow trout reared in the Lees Ferry reach of the Colorado River (Glen Canyon Dam to Lees Ferry) move downstream under some conditions. During FY13–k14, the Natal Origin Research project used a quarterly sampling design (January, April, June-July, and September); however, owing to budgetary constraints the number of research trips may be reduced to three trips in 2015 and 2016. This reduction in field work will reduce other associated project costs (see Project Elements: 5.2.2, 9.1, 9.3, 9.4, 9.7, 9.9, and 9.10).

The analytical methods being developed to assess trout movement use a robust-design (RD, 2 km section) where captured fish are spatially referenced at a 250 m resolution in all sampling reaches (Lees Ferry [R1], House Rock [R2], Buckfarm [R3], Above LCR [R4], and Below LCR [R5]) initially on pass 1, and when recaptured on pass 2 or on other sampling trips. Therefore, emigration losses can be determined based on observations of movement distances of fish released in the RD section and subsequently recaptured at the same or different locations within or across trips. To further supplement this movement information, 2 km sections upstream and downstream of the RD section in reaches R1-3 are sampled. This spatial layout allows us to detect within-reach movements of up to 4 km, but the opportunity to detect shorter movements is greater than for larger ones. Fitting parametric distributions to such data facilitates comparison of movement patterns among reaches and trip intervals, and can also be used to derive a robust estimate of emigration losses for an open population modeling approach like the Jolly Seber (JS) model. Although, the current sampling design allows for estimations of trout movement distances occurring within and across sampling reaches located between Glen Canyon and the LCR; the spatially fixed sampling approach (5-reaches) limits estimations of intermediate movement occurring among tagged trout found between reaches that are not currently sampled. To acquire additional trout movement data for between reach movements of tagged animals, AGFD is planning on conducting mark recapture studies between the five sampling reaches in Marble and Eastern Grand Canyons during FY15–16 (see Project Element 6.4).

The JS model is used to estimate reach-specific abundance, survival and recruitment based on data from the RD mark-recapture sampling design. The apparent survival of marked fish in RD sections based on the decline in recaptures of each marked cohort (a group of fish released in a reach on a given trip) through time. That decline depends on mortality rate as well as loss of fish due to emigration from RD sections. Estimates of movement are required to convert the apparent survival normally estimated by a JS model (which includes losses from mortality and movement) into an actual survival rate, by comparing models where survival rate can vary among trips vs. models where survival is assumed to be constant. Using different modeling approaches allows for estimating abundance at the start of each trip, survival and recruitment between trips, and capture probability for each trip and pass. Parameters of the different models are estimated by minimizing the negative value of the total log likelihood and using the nonlinear search procedure in the AD model-builder (ADMB) software (Fournier and others, 2011). Abundance of unmarked fish at the start of the 1st pass on trips 2 and later depends on abundance at the end of the last pass on the previous trip, and survival and recruitment between trips. Combinations of models (Mt-So, Mtb-So, Mt-S*, Mtb-S*) are being evaluated using Akaike's Information Criteria (AIC, Burnham and Anderson 2002). Model selection, particularly the use of Mb model (behavioral response to capture) types are required because of detection differences for within trip vs across trip. This is likely due to spatial heterogeneity that leads to overestimating capture probabilities and results in an underestimation of trout abundance. These habitat linked differences in fish vulnerability to capture might arise due to fish moving to lower velocity or more protected/shallow habitats, and are to be addressed by some additional habitat assessment (see Project Element 10.1).

Preliminary results from this research study (GCMRC Annual Reporting Meeting, January 2013 & 2014); indicate relatively modest movement of trout between trips with a high proportion of recaptures found in their original release sections, or in adjacent sections, and the vast majority of the recaptures occurring within a 2 km of the original release locations. To date, movement rates into a reach (immigration) rather than out of a reach (emigration) have been considerably less (1/2 the rate observed in 2003) than those reported for previous studies (Coggins 2008; and Coggins and others, 2011) near the LCR. This suggests that the current low immigration rate for trout may be indicative of relatively good conditions for growth in Marble Canyon which could reduce downstream dispersal (see Project Elements 9.3-5, & 9.9), and that movement is more episodic rather than incrementally constant. This is the underlying rationale for such an extended research project (2012–2016). Trout growth is key to interpreting the observed differences in length frequencies and provides the insight on the underlying mechanisms for trout movement. Trout growth is very limited between Sep-Jan and likely most of Jan-Apr period and may be linked to low food availability (hypothesis **H2**) or low feeding efficiency (**H2.1-3**). The differential trout growth as observed among the five RD sections provides insight on understanding what fraction of the Marble Canyon fish immigrate into the LCR inflow reach.

This research project also provides the logistical framework to support the fieldwork necessary for a number of other study projects, these include several project elements in Project 9 "Understanding the Factors Limiting the Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons", Project Element 7.2., "Mainstem monitoring of native and nonnative fishes near the LCR confluence -Juvenile Chub Monitoring" (as per $USDOI_a$ 2011), and Project Element L.2. "Linking invertebrate drift with fish feeding habits." Owing to the extensive tagging effort in this study, other research studies are possible which allow for greater collaboration between these research studies. Currently the NO project provides the logistical framework for data collection and some of the analysis as part of the JCM project (see Project Element 7.2) and other research elements proposed addressing the underlying mechanisms for trout growth and possible movement (see Project Elements: 5.2.2, 9.2, 9.3, 9.4, 9.7, 9.9, and 9.10).

Products expected from this project are a series of peer-reviewed publications.

Project Element 9.3. Exploring the Mechanisms behind Trout Growth, Reproduction, and Movement in Glen and Marble Canyon using Lipid (fat) Reserves as an Indicator of Physiological Condition

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Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research Inc.
Ted Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The objective of this research is to determine whether the ability of adult rainbow trout to acquire and store energy from the prey base is a potential mechanism behind spatial and temporal differences in growth, reproduction, and movement of rainbow trout in Glen and Marble Canyons.

As described in GCMRC's FY13–14 Work Plan (see Project Elements H.2 & L.2.2), rainbow trout size, distribution, diet, and prey base data have been collected for the past two years to examine potential drivers of trout growth, movement, and population size in Glen and Marble Canyons. Continuations of these projects have been requested as part of the FY15–17 Work Plan (see Project Element 9.2), so we propose to add an additional component to this project to quantify lipid (fat) reserves in a subsample of the fish that are already sacrificed to collect data on trout diet. This provides an opportunity to leverage an existing project to gain exciting scientific information in a cost-effective way. Briefly, five sampling reaches downstream from Glen Canyon Dam will be sampled on two separate nights during four seasons over one year. Fish tissue (muscle, liver, hindgut) will be excised, preserved in liquid nitrogen, and brought back to GCMRC for biochemical analysis. In the laboratory, total lipid will be extracted gravimetrically (Bligh and Dyer, 1959; Phillips and others, 1997) and then separated into lipid classes (e.g., non-polar "storage" lipids and polar "structural" lipids) using high-performance thin layer chromatography (Churchward and others, 2008; Zhou and others, 2012). These data will then be used to: 1) examine temporal and spatial differences in the physiological condition of trout in Glen and Marble Canyons; 2) improve rainbow trout growth models currently in development by Korman and Yard; and 3) understand the mechanisms behind the maximum size and growth potential of rainbow trout in Lees Ferry.

Lipid mass data will be examined in combination with growth (mark-recapture data from the whole population; Project Element 9.1), diet (from the same individuals), and drift availability (see GCMRC's FY13–14 Workplan, Project Element F.7.1, FY15–17 Workplan, Project Element 5.2.2*)* to assess how energy availability and storage plays a role in rainbow trout growth, reproduction, and movement across all study reaches during multiple seasons. These data will be especially important in elucidating the mechanisms behind reproduction in Marble Canyon. If adult rainbow trout are critically depleted in lipid mass throughout the growing season (e.g., due to high turbidity in summer) such that energy stores are depleted in fall and spring, there is a high likelihood that fish in Marble Canyon may choose to forgo spawning or reabsorb eggs and gametes to survive (Adams 1999, Hutchings and others, 1994, 1999), which may explain the apparent reduction in local reproduction in lower Marble Canyon by the LCR (Korman and others, 2012).

These data will also be used to improve modeling efforts that assess rainbow trout population dynamics in Glen and Marble Canyons. Korman and Yard have analyzed preliminary data from the Natal Origins project to assess spatial and temporal differences in rainbow trout growth (length and weight; GCMRC Annual Reporting Meeting, January 2014; http://www.usbr.gov/uc/rm/amp/twg/mtgs/14jan30/). However, unexplained patterns in weight loss in the late summer (when the fish should be gaining weight in preparation for winter) indicate the fish may have switched to a fat storage strategy (Adams, 1999), which as described above, would be under-represented in the growth analysis. Models will be improved by incorporating data on spatial and temporal fluctuations in tissue energy density, which is a more reliable indicator of weight gain.

In addition to helping answer mechanistic questions related to rainbow trout growth, these data will also improve our understanding of factors that constrain the maximum size of trout in Lees Ferry. One of the main hypotheses in the FY15–17 Work Plan (**H.2**) was that the size of and species available in the prey base (primarily midges and black flies) support the growth of small rainbow trout but limit the growth of large adult trout. This hypothesis is supported by research conducted by McKinney and Speas (2001) that found that adult rainbow trout are more often food-limited than smaller trout. Rainbow trout, like other temperate fishes, invest in somatic growth (length) prior to investing in visceral (fat) stores, so lipid mass vs. length should show an allometric relationship (Post and Parkinson, 2001; Simpkins and others, 2003). However, preliminary data indicate the opposite, with small fish having larger fat reserves per gram of body tissue than large adult fish (Dibble, unpublished data). Therefore, additional lipid data will be very useful in evaluating the hypothesis that rainbow trout fail to reach trophy status due to a diminished prey base.

Project Element 9.4. Comparative study on the feeding morphology of drift feeding fish

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Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Josh Korman, President, Ecometric Research Inc.

The objective to this project element is to determine if prey retention efficiencies associated with the feeding morphology of rainbow trout, and brown trout are potentially constrained by the size of invertebrate prey available in the CRe. Prey size has a strong effect on foraging success because prey items are not always retained once consumed. In a functional sense, once prey items are captured in the mouth cavity of a fish, water passes through the gill-rakers like a sieve, and prey are retained and ingested. Therefore, branchial arch/gill-raker morphology may control feeding efficiencies (i.e., the number of prey consumed divided by the number of prey captured) such that larger prey items are more often retained than smaller prey. Feeding efficiencies change because morphological structures become larger with increasing fish length (Breck and Gitter, 1983; MacNeill and Brandt, 1990), which cause larger fish to selectively retain only larger prey items (Budy and others, 2005). Therefore, size-related changes in feeding morphology are likely to vary within the same species due to plasticity of morphological traits (Keeley and others, 2007); essentially structural relationships may vary between different environments even though it is the same species. Similarly, these same morphological structures are highly likely to vary among different species, which may be partially responsible for resource partitioning. Lack of prey diversity and minimal prey size in the CRe (Cross and others, 2013) has likely influenced competitive and piscivorous interactions between native and non-native fishes. Findings from these analyses will be used to test hypotheses **H2.1**, **H2.2**, and **H3** (potential for intra- and interspecific competition).

Results from detailed diet analysis from mechanical removal (2003-2004) on rainbow trout (n=1,391) and brown trout (n = 401) (Yard, unpublished) suggest that invertebrate prey availability and prey size; as well as predator size strongly influences feeding success. Aquatic prey items found in the CRe lack taxonomic diversity, these invertebrates consist primarily of a Nearctic dipteran assemblage of small midges and black flies, and a large lentic species of amphipod (*Gammarus lacustris*). Diet for both trout species indicates a high electivity for larger rather than smaller prey items. (An electivity index [E] is based on a scale of 1 to -1, and represents the relative proportion of a diet item to its availability in the drift.) Typically, G. lacustris (E = 0.87; size range 1-12 mm) and black flies (E = 0.55; size range 0.7-5 mm) consume prey in higher proportion than their availability to the drift; however, midges (E = -0.79; size range 0.5-2 mm) and zooplankton (E = -1; size range 0.35-0.7 mm) were consumed less than their availability. Although suspended sediment appears to also negatively affect prey detection for visual sight feeders by reducing food intake (high frequency of empty stomachs during increased turbidity) (unpublished data) (project 9.5 & 9.6), trout size was also negatively correlated with prey food intake (weight of gut contents). Essentially, the difference between observed and expected food intake based on size suggests that the daily rations for trout become limiting for larger sized trout (> 250 mm TL), unless prey availability is limitless. Budy and others (2005) and (Langeland and Nost, 1995) analyses of branchial arch/gill-raker morphology for rainbow and brown trout, respectively, would strongly suggest that prey size and its availability may be a limiting factor on trout growth because of feeding inefficiencies with increasing trout size.

In this study, we propose to (1) measure gill-raker number, length, and spacing for two drift feeding species: rainbow trout and brown trout; (2) develop and compare branchial arch and gill-raker morphology within and among fishes; (3) determine if mean prey size distributions found in fish diet correlate with morphometrics (i.e., method of quantifying a structure through measurements of size, shape, and quantity); (4) and determine if diet electivity for prey size distributions are proportionally greater in the fish diet than what is found available in the drift. Exploring these other types of quantitative methods may further reduce the amount of analytical time and cost associated with conducting these types of morphometric measurements.

Invertebrate drift and diet samples for rainbow and brown trout have been and are continuing to be collected as part of the Foodbase Monitoring project (see GCMRC's FY13–14 Workplan, Project Element F.7.1). For each fish species, we will evaluate a large size distribution (~50 to 400+ mm fork length) and develop relationships between fish size and morphological characteristics. The minimum fish size has yet to be determined because of developmental differences in feeding structures. For comparative purposes, morphological data will be paired with detailed diet analysis (prey size and prey densities), using a subset of fish samples containing both branchial arches and stomach contents. For the fish length relationships we will select and measure three fish per size class, with samples grouped at 5 mm increments. This project will produce one manuscripts, suitable for publication. Expected timeline for project completion is 2017.

Project Element 9.5. Meta-analysis, and the development of reactive distance relationships for encounter rate models

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Josh Korman, President, Ecometric Research Inc.
Charles Yackulic, Research Statistician, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC

The objective of this project element contains two parts: (1) determine the effects of varying light intensity and prey size on fish reactive distances; and (2) develop an encounter rate model for drift feeding fish that accounts for varying reactive distances and prey availability within the range of channel depths and light levels encountered in Glen and Marble Canyons.

Underwater light intensities are likely to interact with different prey sizes because larger rather than smaller items are perceived at greater distances. Reactive distance relationships have been developed for a number of fish species (e.g., Howick and Obrien, 1983; Vinyard and O'Brien, 1976; Ware, 1973); however, inconsistencies exist in the literature. This is partly due to the scope and range of variables experimentally tested, particularly with the use of turbidity as a predictive proxy for light (e.g., Barrett and others, 1992; Sweka and Hartman, 2003). Considering that underwater light intensities change over the day and with increasing depth, most turbidity-based relationships are limited in application to small, clear, and shallow (depth < 0.5 m) streams. There are however a number of existing models that have been developed specifically for the CRe that account for variation in light reaching the water surface due to canyon topography (Yard and others, 2005) as well as predictive relationships between the underwater light attenuation and suspended sediment (Yard, 2003).

We will conduct an extensive meta-analysis on all known published data on reactive distances (i.e., distance a prey item can be visually detected) of visual sight-feeding fish. We will evaluate literature and quantitatively summarize regression slopes obtained from independent studies, either published as relationships or through extraction of data from graphs and tables (Tummers, 2006). Through this meta-analysis we are going to refine the predictive capabilities of these reactive distance relationships so that they can be broadly applied to more realistic environmental conditions. We will evaluate specific variables that affect predator reactive distances, including light intensity, turbidity, prey size, and predator size. Findings from this data synthesis will inform the process used in selecting or developing the most appropriate relationships to use in developing an encounter rate model (i.e., quantifying the daily number of drifting invertebrates encountered by a visual sight feeding fish; Gerritsen and Strickler, 1977; Harvey and Nakamoto, 2013). From this analysis, the type of encounter rate model selected will be a critical element for developing an accurate bioenergetic model capable of linking drift-availability and metabolic demands thought to limit overall fish growth in a seasonally turbid river (see project 9.7).

Data sets from both long-term monitoring and research studies will be used for developing an encounter rate model for rainbow trout. These data requirements include seasonal variation in invertebrate drift (Project Element 5.2.2), and other physical data such as instantaneous light intensities (Yard and others, 2005), channel characteristics, flow discharge, and suspended sediment concentrations (http://www.gcmrc.gov/discharge_qw_sediment/). Encounter rates will be determined for five specific study reaches (NO reach designation) located between Glen

Canyon and the LCR confluence area. We will model the potential influence that reduced light levels have on the frequency of trout daily encounter rates (mediated through differences in channel depths, turbidity levels, and invertebrate drift). Findings from these analyses will be used to test hypothesis **H2.3**, as well as compare responses to other independent data on trout diet (see Project Element 5.2.2.), monthly growth rates (see Project Element 9.2), and physiological condition (see Project Element 9.3). Results from this will determine whether or not reduced encounter rates exert a population-level effect on rainbow trout throughout Glen and Marble Canyons. This project will produce two manuscripts, each suitable for publication. Expected timeline for project completion is 2017.

Project Element 9.6. Evaluation of Turbidity (in terms of TSS) as a potential Glen Canyon Dam operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub

David Ward, Fishery Biologist, USGS, GCMRC

The objective to this project element is to determine what level and duration of turbidity would be necessary to negatively effect, or prevent persistence of, rainbow trout in lower Marble Canyon and below the Little Colorado River confluence in eastern Grand Canyon. This project aims to determine whether turbidity levels in the Colorado River could be manipulated during years of minimum annual release, coincident with Paria and Little Colorado River fine-sediment inputs, so as to limit survival of rainbow trout downstream of the these tributaries.

Predation on juvenile humpback chub by rainbow trout is considered a significant threat to humpback chub populations in Grand Canyon (Marsh and Douglas, 1997; Coggins and others, 2011; Yard and others, 2011; Runge and others, 2011). Relatively low levels of turbidity <100 Formazin Nephelometric Units (FNU) have been found to effectively reduce vulnerability of juvenile humpback chub to predation by rainbow trout (Ward, 2014 AMWG poster session, unpublished data), and extended periods of turbidity have been shown to negatively impact and exclude salmonids in other systems (Harvey and Railsback, 2011, reviewed in Newcombe and MacDonald, 1991). Increasing turbidity can also have positive effects on small species and juvenile fish but a negative effect on larger piscivorous fishes (Utne-Palm, 2002). Understanding how the magnitude and duration of turbidity in the Colorado River impacts various life stages of rainbow trout will allow researchers to better evaluate turbidity as a potential management tool of juvenile humpback chub in Marble and eastern Grand Canyons.

This project is intended to evaluate the feasibility of using turbidity as a management tool to disadvantage trout populations in the mainstem Colorado River below the Paria River and Little Colorado Rivers. In the laboratory, we will evaluate the effects of multiple turbidity concentrations (50–200 FNU) and extended high turbidity durations (1–5 months) to identify turbidity thresholds that negatively impact rainbow trout and reduce survival. LISST-100 instrumentation will be used in combination with YSI turbidity probes to compare the level of FNUs to total suspended sediment concentration and grain size distributions in controlled tank experiments (Voichick and Topping, written commun., USGS, 2014). This information will allow for science based, data driven discussions of possible annual-to-multiyear scenarios for seasonal dam operations under minimum annual release volumes from Lake Powell that may allow levels of turbidity associated with natural tributary sediment inputs to be used as a fish management tool.

Understanding how turbidity impacts rainbow trout is critical in evaluating flow and exotic fish control management options aimed at preservation of native fishes in Grand Canyon. Runge and others, (2011) in assessing 19 options for mitigating the negative influence of rainbow trout on humpback chub identified sediment augmentation from sources in Lake Powell to Lees Ferry as likely the most effective treatment for reducing trout predation on chub juveniles, and numerous studies (Reviewed in Newcombe and MacDonald, 1991) demonstrate that relatively low sediment concentrations can adversely impact rainbow trout populations. Questions regarding effects of turbidity on fish are difficult to answer in a field setting because of confounding factors and the often extended time periods needed to evaluate turbidity effects, but these types of interactions can often effectively be evaluated in laboratory settings (Hairston, 1989). Previous discussions about sediment augmentation below Glen Canyon Dam were aimed at restoring both sand and finer sediment to the river to benefit native fish, as well as sandbars, which was cost prohibitive, but small scale silt and clay augmentation that only increase turbidity slightly may be just as effective at reducing predation mortality of native fish and was identified by Randle and others, (2007) as much less costly than sand augmentation. Seasonally focused flow management efforts to increase turbidity within the Colorado River may be a much more cost effective and acceptable solution than downstream mechanical trout removal (Coggins and others, 2011) as a means to reduce predation and competition on juvenile humpback chub, particularly during periods when dam releases are naturally warmer at the LCR; a condition known in 2011 to be associated with reduced juvenile chub annual survival (possibly, linked to increase trout metabolism; see Keiffer and others, 1994). This project will allow an assessment of turbidity as a trout management tool, from a laboratory experimental perspective.

Project Element 9.7. Application of a bioenergetics model in a seasonally turbid river

Michael Dodrill, Fishery Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.

The objective to this project element is to adapt process-oriented ecological models (such as drift-foraging bioenergetics or net energy intake methods) to quantify the effects of physical conditions (i.e., flow, turbidity, and depth) and food availability on rainbow trout growth and distribution.

Understanding the linkages between food availability and growth of drift feeding fish in large regulated rivers presents significant challenges to scientists and managers. Process-oriented ecological models show promise for describing ecological dynamics in rivers across levels of biological organization (Anderson and others, 2006). Linked foraging-bioenergetics or Net Energy Intake (NEI) models explicitly consider physical habitat (depth, velocity) and ecological processes (drift-availability) to describe the foraging process and how food availability translates into fish growth. These methods have been used to assess the effects of invertebrate drift size structure on the lifetime growth of drift-feeding fish (Hayes and others, 2000), assess habitat, and provide an alternative to traditional approaches (i.e., PHABSIM) for predicting the response of fish changes in physical conditions, such as altered flow regimes (Rosenfeld and Ptolemy, 2012) or turbidity levels (Harvey and Railsback, 2009).

Building on preliminary methods developed for Lees Ferry (Dodrill, unpublished data), coupled drift-foraging bioenergetics have identified linkages between drift-availability and metabolic demands thought to limit overall fish growth. Benthic invertebrates are the ultimate source of drift consumed by rainbow trout and contribute to the spatial patterns of drifting invertebrates. Understanding factors that influence the spatial and temporal dynamics of invertebrate drift and physical factors (such as turbidity or flow conditions) that influence the detection of food items (Project Element 9.5) will help to correlate patterns of rainbow trout growth and abundance (Project Element 9.2) to underlying mechanisms. We propose integrating data sourced from existing and proposed projects to develop and parameterize process-oriented models. This includes information on invertebrate drift rates (Project Element 5.2.2), channel characteristics (Project Element 10.1), turbidity, and temperatures for river segments extending from Lees Ferry to the LCR.

Project Element 9.8. Mechanisms that Limit Rainbow and Brown Trout Growth in other Western Tailwater Systems

Kimberly Dibble, Research Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Ted Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Phaedra Budy, Research Aquatic Ecologist, USGS, Utah Coop. Fish and Wildlife Research Unit
Michael Dodrill, Fishery Biologist, USGS, GCMRC

The objective of this research is to continue to develop a broader understanding of the links between dam operations and salmonid population dynamics by synthesizing data from tailwaters across the Western United States.

Under Project H.2 of GCMRC's FY13–14 Workplan, the principal investigator amassed fishery, discharge, reservoir, food base, and other data from 56 dams throughout the West. We are in the process of analyzing this dataset and continued funding will maximize the degree to which the GCDAMP can learn from other tailwater ecosystems. The analysis presented at GCMRC's Annual Reporting Meeting (January 2014) was an appropriate first step at synthesizing these data and addressed one of the four main hypotheses (**H4**) related to changes in trout size over time relative to dam operations. This analysis focused on the influence of hydropeaking, seasonal flow, specific discharge, and other metrics on trout size, recruitment, and catch-per-unit-effort downriver of dams with multiple purposes (e.g., hydropower, irrigation, and storage). This analysis allowed us to understand broad correlations between dam operations and aspects of trout populations across many dams and we are in the process of preparing a manuscript based on these results, which will be submitted for publication in FY14.

We propose to complement this broad assessment with in-depth analyses of tailwaters that contain a rich time-series of information. This new set of analyses will be focused on assessing the mechanisms behind salmonid growth as they relate to dam operations (e.g., prey availability, temperature, nutrients) using a subset of high-quality fishery data from the Colorado River Basin that spans 20+ years. For example, does discharge volume and/or hydropeaking directly influence trout size, or does discharge indirectly influence trout size through another variable (e.g., prey availability or nutrient inputs from the reservoir). Since all the data for this analysis are already collected, we expect to begin our work within FY14, with the expectation that it will spill over into FY15. We will prepare one manuscript for publication associated with the new analysis in FY15.

In addition to the mechanistic model developed in FY15, we propose to apply bioenergetics models developed for rainbow trout in Glen and Marble Canyon to other data-rich tailwaters in the Colorado River Basin (CRB) to further elucidate mechanisms responsible for differential performance on trout fisheries. By applying the same modelling format to different tailwaters, it should ease our ability to interpret differences between Glen Canyon and other tailwater systems.

We have high-quality fishery, growth, foodbase, temperature, discharge, and reservoir data from Flaming Gorge Dam, which is the system that is most comparable to Glen Canyon Dam in the CRB. However, it differs from Glen Canyon because it has a selective withdrawal device that allows modification of the thermal regime (a phenomenon that may occur naturally below Glen Canyon resulting from climate change), it differs in invertebrate composition, and its trout population is composed of >50% brown trout. Brown trout are highly efficient predators (Yard and others, 2011), and their population expansion has been of concern in the Colorado River downriver of Glen Canyon Dam. Therefore, we propose to develop a bioenergetics model for the Flaming Gorge tailwater that is similar to the model currently being developed for Glen Canyon, which will examine how prey size, water velocity, temperature, and rainbow and brown trout density (competition) influence the growth potential of rainbow trout. In addition, we may also construct a bioenergetics model for the tailwater below Navajo Dam. The Navajo tailwater lacks thermal modification and differs from Glen Canyon and Flaming Gorge in its flow regime (no hydropeaking), invertebrate assemblage, and brown trout density (~39%). Comparison of Glen Canyon to other tailwaters from a bioenergetics perspective will yield important insights that will be useful in the management of Glen Canyon Dam operations. We will prepare one manuscript in FY16 associated with these bioenergetics models.

Project Element 9.9. Effects of High Experimental Flows on Rainbow Trout Population Dynamics

Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.
Charles Yackulic, Research Statistician, USGS, GCMRC
Ted Melis, Physical Scientist, USGS, GCMRC
Dan Buscombe, Research Geologist, USGS, GCMRC
Thomas Gushue, Computer Specialist, USGS, GCMRC

The objective to this project element is to determine the effects of fall HFEs and other potential management actions, such as the Fall Steady Flow treatments of 2011–12, on rainbow trout populations in Glen Canyon. The purpose of the contingency plan as originally proposed (GCMRC FY13–14 Workplan, Project Element H.3) was to determine the effect of a single fall HFE on age-0 trout densities. Although spring floods were known to have a large effect on early life stages of age-0 trout (Korman and Campana, 2009), there was considerable uncertainty about the effect that fall floods had on the survival of age-0 trout due to seasonal differences in growth (Melis and others, 2012). Typically, age-0 fish have a higher mortality rate than adults, yet rates begin to stabilize through late-summer into fall (Korman and others, 2011). The experiment was originally designed to estimate age-0 trout density and survival during pre- and post-flood periods, and then compare estimates between years with and without experimental floods. Currently we have successfully estimated changes in the apparent survival across two successive HFEs, flow events that had different magnitudes and durations, but due to hydrology we have been unable to acquire data during a year without an experimental flow.

The sampling design uses two mark-recapture trips that are conducted annually during early- and late-fall and samples the entire 25 km reach between Glen Canyon Dam and Lees Ferry. On average a total of ~5,000 fish are tagged with passive integrated transponders (PIT tags) per trip to determine site-specific capture probabilities for estimating age-0 fish abundance. A second trip is repeated in late-fall, to estimate across-trip survival and growth using recapture information from the previous trip. Although age-0 trout densities were estimated to be very high at the inception of the research study (fall 2011) successive marking efforts conducted in 2012 and 2013 have each required an additional 10-day sampling trip per year to tag sufficient numbers of trout (~10,000 age-0 trout quota) for the Natal Origin Project (see Project Element 9.2). For this reason we propose a continuation of funding for fall marking trips through FY16, when at that time the Natal Origins research project will transition to monitoring led by AGFD. Funding for this project will support additional fieldwork and tagging efforts necessary for meeting the Natal Origin research objectives, as well as providing a means to further evaluate multiple fall-HFEs over a range of different age-0 fish densities. Also, efforts were started in fall 2013 to assess change in Glen Canyon channel-bed texture (Natal Origins Reach 1) in response to August 2013 fine-sediment inputs to that reach from Waterholes Canyon (the reach being imaged with side-scan sonar in October and December 2013 to bracket the November 2013 HFE, as well as in April 2014 to assess evolving shorelines and bed textures relative to ongoing trout monitoring and research.

Project Element 9.10. Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon

Kimberly Dibble, Research Biologist, USGS, GCMRC
Luke Avery, Fishery Biologist, USGS, GCMRC
Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The objective of this research is to quantify the effect of lower and steadier fall flows (~5,000 ft^3/s) followed by an HFE on the physiological condition and growth of age-0 and adult rainbow trout in Glen Canyon.

In fall 2012 and 2013, the Federation of Fly Fishers raised concerns regarding the potential effects of lower and steadier fall flows followed by an HFE on the foodbase for rainbow trout in Glen Canyon. Although previous research indicates that steadier flows can increase the growth rate of age-0 rainbow trout (Korman and Campana, 2009), and spring-timed HFEs can increase their survival and growth (Korman and others, 2011), it is unclear how lower and steadier fall flows (5,000-8,000 ft^3/s) followed by a potentially energetically costly HFE may influence the growth and physiological condition of rainbow trout during a season where prey are typically limited. It is also unclear how quickly the trout population recovers following such an event, and whether the response for age-0 and adult fish differs. Therefore, this research will assess rainbow trout condition by using total lipid mass and lipid classes (e.g., storage fats, triacylglycerols) as sensitive biochemical indicators of physiological condition. In addition, otoliths of age-0 rainbow trout will be collected in post-flood fish to examine their daily growth rate in the weeks prior to and following an HFE to assess response and recovery time. These data will be compared to food base data collected prior to, during, and after the HFE. In addition, data will be collected in fall during a non-HFE year to compare rainbow trout condition and growth in a normal year to those influenced by an HFE.

Field sampling to collect fish will largely be incorporated into existing research and monitoring trips (Project Elements 6.7 [RTELSS], 9.2 [Natal Origins], and 9.9 [HFE/Fall Marking]), but additional electrofishing trips may be necessary. Total lipid will be extracted gravimetrically from whole-body age-0 fish and from adult tissue samples (Bligh and Dyer, 1959; Phillips and others, 1997), and total lipid will be separated into lipid classes using high-performance thin layer chromatography (Churchward and others, 2008; Zhou and others, 2012).

Otoliths will be extracted from age-0 rainbow trout (Secor and others, 1991) collected during an HFE year and prepared for growth rate analysis using the distance between daily increments pre- and post-flood (Gilliers and others, 2004; Amara and others, 2009). In addition, age-0 otoliths will be checked for a "check" (a dark line indicating daily growth rings are placed very close together) to determine whether growth is interrupted in response to environmental conditions prior to and during the HFE. Growth rate measurements will be compared to those from fish captured during a non-HFE year to account for normal seasonal fluctuations in growth that occur regardless of the occurrence of a controlled flood.

D.2 Personnel and Collaborations

The overall project lead for Research Project 9.0 is Dr. Michael Yard a fishery biologist with U.S. Geological Survey, Grand Canyon Monitoring and Research Center (GCMRC). Dr. Josh Korman a fishery biologist with Ecometric Research Inc., and is the principal investigator for the Natal Origin Project (9.2) specializing in analytical models and database development, population dynamics, and modelling capabilities. Dr. Kim Dibble is a post-doctoral fellow and research biologist at GCMRC with expertise in fish physiology and metadata analysis. Dr. Charles Yackulic is a research statistician specializing in population dynamics with an emphasis in modeling linkages and vital rates between trout populations. Dr. Theodore Melis is a physical scientist and will be instrumental in assessing changes in channel-bed texture and relationships among fish communities. Daniel Buscombe is a post-doctoral fellow and Research Geologist with specialization in image processing and bed-texture characterization. Thomas Gushue is a GIS specialist, expert in collecting, processing, and analyzing digital elevation models.

D.3 Deliverables

Journal articles will be prepared in FY15–17 covering several of the following components of this project:

- Factors leading to differential growth in rainbow trout (*Oncorhynchus mykiss*) in the Colorado River, Grand Canyon.
- Experimental flood effects on age-0 rainbow trout in the Colorado River, Grand Canyon.
- Analytical methods using a modified open robust design: estimation of rainbow trout abundance in a large spatially complex river.
- Using a hierarchical Bayesian model: estimating age-0 rainbow trout abundance in the Lees Ferry sport fishery.
- Estimating rainbow trout (*Oncorhynchus mykiss*) emigration using capture-recapture data with open robust design models

E. Productivity from Past Work (during FY 13–14)

E.1. Completed Publications

Kennedy, T.A., Yackulic, C.B., Cross, W.F., Grams, P.E., Yard, M.D., and Copp, A.J., 2013, The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river, Freshwater Biology, v. 59, p. 557-572.

Ward, D.L., Morton-Starner, R., and Hedwall S.J., 2013, An evaluation of liquid ammonia (ammonium hydroxide) as a candidate piscicide, North American Journal of Fisheries Management, v. 33, p. 400-405.

Yackulic, C.B., Yard, M.D., Korman, J., and Van Haverbeke, D.R., 2014, A quatitative life history of endangered humpback chub that spawn in the Little Colorado River: variation in movement, growth, and survival: Ecology and Evolution, doi: 10.1002/ece3.990.

E.2. Publications in progress

Dibble, K.L., Yackulic, C.B., Kennedy, T., and Budy, P., Factors that limit salmonid size in tailwater fisheries across the western United States.

Ward, D.L., and R. Morton-Starner. In prep. Effects of turbidity on predation vulnerability of humpback chub to rainbow trout and brown trout.

Yard, M.D., Coggins, L.G., Kennedy, T., and Yackulic, C.B., Effects of turbidity on foraging ecology of nonnative rainbow trout and brown trout

E.3. Presentations at GCDAMP meetings

Dibble, K.L., Yackulic, C.B., Kennedy, T., and Budy P., 2014, Context and comparison: status of tailwater fisheries in the Western United States: Annual Reporting Meeting to the Adaptive Management Program for Glen Canyon Dam. Phoenix, AZ, 1/28/2014.

Korman, J., and Yard, M., 2014, Rainbow trout movement, growth, population dynamics and modeling in Glen and Marble Canyons: Annual Reporting Meeting, Adaptive Management Program for Glen Canyon Dam, Phoenix, AZ, 1/28/2014.

Melis, T.S., Gushue, T., Kennedy, T.A., Muehlbauer, J.D., Yard, M.D., Grams, P.E., Sankey, J.B., Kohl, K., Andrews, T., Hazel, J.E., Jr., and Korman, J., 2014, Low flows in Glen Canyon, preliminary geomorphic analysis of the potential effects on fish and foodbase: Annual Reporting Meeting to the Adaptive Management Program for Glen Canyon Dam. Phoenix, AZ, 1/28/2014.

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Ward, D.L. and R. Morton-Starner (2014). Effects of turbidity on predation vulnerability of humpback chub to rainbow trout and brown trout: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, AZ. POSTER – TWG and AMWG meetings.

Yackulic, C., Yard, M.D., Korman, J., Van Haverbeke, D.R., and Coggins, L., 2014, Results from Colorado River study site and ongoing population modeling: Annual Reporting Meeting , Adaptive Management Program for Glen Canyon Dam, Phoenix, AZ, 1/28/2014.

E.4. Presentations at professional meetings

Avery, L., Korman, J, and Copp, A., 2013, Flow related responses of the age-0 population of rainbow trout in Lees Ferry, Desert Fishes Council, Flagstaff, AZ. 11/20/13.

Dibble, K.L., Yackulic, C.B., Kennedy, T., and Budy, P., 2013, What factors drive salmonid growth in tailwater ecosystems? A synthesis of data on salmonid population dynamics and dam operations across the Western United States, Annual Colorado River Fish Cooperator's Meeting, Flagstaff, AZ, 12/19/2013.

Dibble, K.L., Yackulic, C.B., Kennedy, T., Budy, P., and Korman J., 2013, What can we learn from other tailwaters? A synthesis of data on salmonid population dynamics and dam operations across the Western United States, 12th Biennial Conference of Science and Management on the Colorado Plateau, Flagstaff, AZ, 9/18/13.

Dibble, K.L., 2013**,** Telling tall tales? Teasing out the mechanisms behind changes in trout size over time in western tailwaters, Watershed Sciences Department, Utah State University,

Logan, UT. 5/8/13.

Dodrill, M., Pine, B., Gerig, B., and Finch, C., 2013, Steady as she flows: assessing the response of native fish to a steady flow experiment from Glen Canyon Dam, Desert Fishes Council, Flagstaff, AZ. 11/20/13.

Rogowski, D., 2013, Does variation in sampling effort during a long term monitoring project matter (Lees Ferry, Colorado River)?, Desert Fishes Council – Flagstaff, AZ. AZ. 11/20/13.

Morton-Starner, R., and Ward, D.L., 2014, An experimental evaluation of competition between rainbow trout and humpback chub. Desert Fishes Council – Flagstaff, AZ.

Ward, D.L., and Morton-Starner, R., 2014, What environmental factors reduce predation vulnerability for native fish? Colorado River Area Biologists Meeting, Laughlin, NV.

Ward, D.L., and Morton-Starner, R., 2014, Effects of water temperature and turbidity on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout. Desert Fishes Council – Flagstaff, AZ. AZ. 11/20/13.

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Yackulic, C., Yard, M., Korman, J., and Vanhaverbeke, D.R., 2013, A quantitative life history of humpback chub that spawn in the Little Colorado River: variation in movement, growth and survival, Desert Fishes Council, Flagstaff, AZ. 11/20/13.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$483,200**	**$9,000**	**$94,800**	**$162,400**	**$190,000**	**$0**	**$122,900**	**$1,062,300**
X	X			X			9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$41,100	$0	$0	$12,900	$115,000	$0	$11,900	$180,900
	X			X			9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$95,700	$0	$14,900	$127,400	$75,000	$0	$39,500	$352,500
				X			9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$48,500	$0	$40,000	$0	$0	$0	$13,800	$102,300
				X			9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$72,100	$0	$2,400	$0	$0	$0	$11,600	$86,100
				X			9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$29,200	$2,500	$1,500	$0	$0	$0	$5,200	$38,400
				X			9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$27,500	$2,000	$2,500	$0	$0	$0	$5,000	$37,000

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
				X			9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$53,800	$2,000	$1,500	$0	$0	$0	$9,000	$66,300
				X			9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$58,400	$2,500	$1,500	$0	$0	$0	$9,800	$72,200
	X			X			9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$12,500	$0	$28,000	$22,100	$0	$0	$9,800	$72,400
				X			9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$44,400	$0	$2,500	$0	$0	$0	$7,300	$54,200

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY16																	
							9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$483,600**	**$7,500**	**$87,500**	**$168,400**	**$190,000**	**$0**	**$165,100**	**$1,102,100**
X	X			X			9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$62,300	$2,500	$0	$12,900	$115,000	$0	$20,000	$212,700
	X			X			9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$100,500	$0	$50,100	$145,500	$75,000	$0	$65,400	$436,500
				X			9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0
				X			9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$80,000	$2,500	$2,400	$0	$0	$0	$18,100	$103,000
				X			9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$29,800	$0	$1,500	$0	$0	$0	$6,700	$38,000
				X			9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$21,400	$0	$2,500	$0	$0	$0	$5,100	$29,000

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY16																	
				X			9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$56,100	$0	$1,500	$0	$0	$0	$12,300	$69,900
				X			9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$65,600	$0	$1,500	$0	$0	$0	$14,300	$81,400
	X			X			9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$12,900	$0	$28,000	$10,000	$0	$0	$10,900	$61,800
				X			9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$55,000	$2,500	$0	$0	$0	$0	$12,300	$69,800

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY17							
							9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$357,600**	**$0**	**$86,000**	**$123,700**	**$50,000**	**$0**	**$156,700**	**$774,000**
X	X			X			9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$60,400	$0	$0	$0	$0	$0	$16,500	$76,900
	X			X			9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$98,600	$0	$50,100	$101,600	$50,000	$0	$70,000	$370,300
				X			9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0
				X			9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$70,000	$0	$2,400	$0	$0	$0	$19,800	$92,200
				X			9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$25,700	$0	$1,500	$0	$0	$0	$7,400	$34,600
				X			9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$20,900	$0	$2,500	$0	$0	$0	$6,400	$29,800

Monitoring		Research																
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
				X			9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$50,800	$0	$1,500	$0	$0	$0	$14,300	$66,600
				X			9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0
	X			X			9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$27,200	$0	$28,000	$22,100	$0	$0	$21,200	$98,500
				X			9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$4,000	$0	$0	$0	$0	$0	$1,100	$5,100

Project 10. Where does the Glen Canyon Dam rainbow trout tailwater fishery end? - Integrating Fish and Channel Mapping Data below Glen Canyon Dam

Initial Estimate: FY15: $148,600; FY16: $163,500; FY17: $132,200

GCDAMP Funding: FY15: $148,600; FY16: $152,100; FY17: $125,600

A. Investigators

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B. Project Summary

Glen Canyon Dam's rainbow trout tailwater fishery (hereafter, GCD tailwater) begins in the project's tailrace, but where does it end? The serial discontinuity concept for impounded rivers was first described by Ward and Stanford (1983), whereby recovery of river ecosystems impaired by dams is predicted to increase with distance below dams; often influenced by locations of downstream tributaries that to some degree add back resources lost to upstream reservoirs. The Colorado River ecosystem (CRe) is composed of several river segments extending from the forebay of GCD to the western boundary of GCNP, and has been studied extensively for the past five decades (Gloss and others, 2005; Schmidt and Grams, 2011a). However, it remains unclear how long-term trends in the river's channel morphology in response to dam operations, will combine with climate-change induced trends in downstream quality-of-water (QW) to influence the exotic rainbow trout tailwater fishery and native fish in the CRe. Stream forecasting under current climate change for the southwestern US and Colorado River suggests dryer conditions are already occurring under global warming (see chaps. 8 & 20 of the 2014 National Climate Assessment: http://nca2014.globalchange.gov/report).

Reduced water storage in Lake Powell since 2001, has already resulted in warmer GCD releases; a trend that has significantly influenced the discontinuity distance and recovery relative to the river's altered thermal regime in Grand Canyon over the last 14 years. Whether exotic or native fish species in GCNP will benefit more from these somewhat warmer, but still unnaturally cold releases under both drier and warmer conditions below GCD remains highly uncertain. Located 15 miles below GCD, the confluence with the Paria River is typically referred to as the downstream terminus of the "Lees Ferry" recreational trout fishery, and is also the approximate boundary between Glen Canyon National Recreation Area and Grand Canyon National Park (GCNRA and GCNP, respectively). However, rainbow trout are also found below the Paria and Little Colorado Rivers, more than 75 miles downstream of the dam (Makinster and others, 2010). Recent modeling studies suggest that sand-sized sediment can be a significant limiting factor in the spawning success of trout in gravel-bed settings, and may be more important than finer sediments in limiting flow and reducing levels of dissolved oxygen needed by incubating trout eggs within redds (Pattison and others, 2012; Sear and others, 2012). The highly sporadic and intermittent nature of flooding and sediment production from the Paria River results in periods when the Colorado River's bed and water quality may or may not be greatly affected by fine-sediment deliveries from this important tributary. Paria River flow volumes are relatively small and typically have little influence on the now-altered temperature regime of the Colorado River below Glen Canyon. Therefore, the effective "discontinuity distance" below GCD may be highly variable through time relative to the Paria River's location below the dam.

Ellis and Jones (2013) conclude that at least two recovery gradients exist in regulated rivers, with the thermal recovery gradient typically being the longest. To improve understanding about discontinuity distance(s) associated with the GCD tailwater, this interdisciplinary research project proposes to integrate new and existing channel mapping methods with ongoing fisheries monitoring and analyses using a variety of information about the geometry of channel margins, bed-sediment characteristics (softer (sand and finer) and harder (gravel or bedrock) substrates), and quality of water (QW) data (including, flow, water temperature and turbidity or total suspended sediment). This project's aim is to evaluate the potential effects of physical processes (water temperature and sediment input frequency) on native and nonnative fish dynamics. The basic questions being asked are: 1) How do seasonal fine-sediment inputs, high flow events and dam release temperatures affect downstream spawning for rainbow trout, and rearing habitat for trout and humpback chub? and, 2) Do fall-timed pulse flows extend the rainbow trout fishery downstream toward or beyond the Little Colorado River? Sources of information needed to address these questions are shown in figure 1.

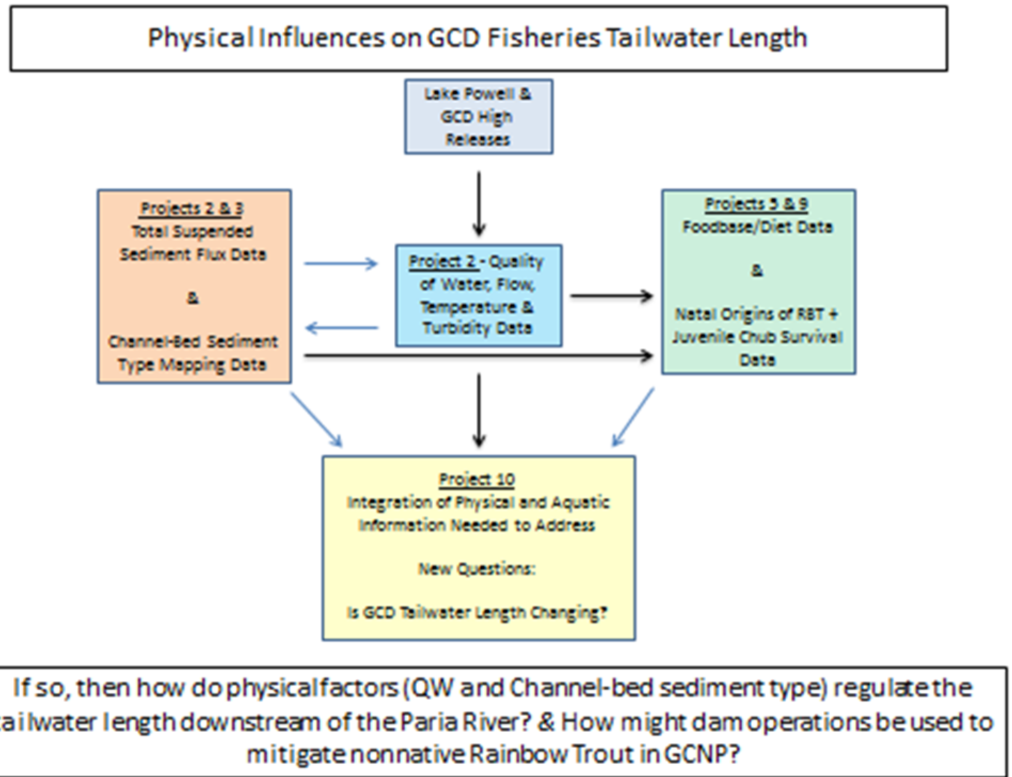

Figure 1. Sources of existing and new information from ongoing GCMRC monitoring and research projects that are available to answer new ecologically important questions about GCD operation and co-management of native and nonnative fish in GCNRA and GCNP. The CRe's thermal recovery gradient has moved upstream since 2002, in response to reduced Lake Powell storage, while highly variable point sources of fine sediment influencing turbidity remained fixed.

This information has management implications, particularly below GCNRA where rainbow trout are of concern relative to native fish conservation in GCNP. Understanding the relationships between trout life history, and abiotic and biotic processes affected by specific dam operations and climate change will provide greater insight about strategies for co-managing native and nonnative fisheries between Lakes Powell and Mead. Project findings may also be transferable to inform management of other Colorado River basin tailwaters where similar challenges in co-management of native and nonnative sport fisheries exist (see Trammel, 2010; Clarkson and Marsh, 2010).

As shown in figure 1, this project intends to build on the numerous recent achievements of several FY13–14 projects, including near real time monitoring of flow, QW and suspended-sediment transport (Topping and others, Project 2), annual channel mapping of sandbars (Grams and others, Project 3), quarterly monitoring of natal origins (NO) of rainbow trout and humpback chub juvenile survival (Korman and Yard, Project 9), and ongoing monitoring of the CRe's food base (Kennedy and others, Project 5). Proposed interdisciplinary analyses of fish and channel-map data also critically depend upon the capabilities of the GCMRC's GIS Services and Support project, as well as GCMRC's abundant existing remote sensing data (Gushue and others, Project 14).

We propose to use both new and existing channel mapping data (Table 1) to advance an integrated physical and biological outcome that is only possible owing to ongoing QW and channel monitoring, as well as NO and food base field monitoring during 2015-16. Outcomes from other monitoring projects focused on riparian vegetation and cultural resources (Projects 11 and 12) will also be considered in terms of channel-shoreline changes in NO study reaches as appropriate and available during project synthesis in 2017.

Table 1. Existing and ***Proposed*** channel-bed bathymetry and bed-sediment imagery data needed for integrated analyses with biological data from Natal Origins of Rainbow Trout & Juvenile Humpback Chub Survival (NO, Project 9) study reaches

Water Year (WY) / Month(s) data collected/ Annual Release Volume (maf)/ Types of dam operations	**NO Reach #1 (rms -6 to -2)**	**NO Reach #2 (rms 16 to 20)**	**NO Reach #3 (rms 37 to 41)**	**NO Reach #4a (rms 60 to 61)**	**NO Reach #4b (rms 62 to 64)**
WY2016/ annual volume & operations are not projected yet	***HSS (SEP & APR)***	***MBB/AB (MAY) + HSS (SEP & APR)***	***HSS (SEP & APR)***	****MBB/AB & HSS (APR, *JUL & SEP)***	***HSS (APR & SEP)***
WY2015/ *projected* ~9.0 maf/ Modified Low Fluctuating Flows (MLFF)	***MBB/AB (NOV or AUG)***	***HSS (APR & SEP)***	***HSS (APR & SEP))***	****MBB/AB & HSS (APR, *JUL & SEP)***	***HSS (APR & SEP)***
WY2014/ 7.48 maf/ MLFF & fall HFE	HSS (APR)	***HSS (SEP)***	***HSS (SEP)***	HSS (APR), MBB/AB (MAY)	HSS (APR), MBB/AB (MAY)
WY2013/ 8.23 maf/ MLFF & fall HFE	HSS (OCT & DEC)	HSS (MAY)	n.d.	MBB/AB (AUG)	n.d.

WY2012/ 9.47 maf/ MLFF & fall steady flow test (OCT 2011)	n.d.	n.d.	MBB/AB/HSS	MBB/AB/HSS	n.d.

KEY – n.d., No data, HSS, Humminbird sidescan sonar imagery; MBB/AB, Multi-beam bathymetry/acoustic backscattering imagery; TSS, Towed sidescan imagery (Klein® system, digital, duel frequency, UWV, Underwater video, AHGI, 2003, Airborne, high-gain digital imagery). *, Collection of these data contingent upon funding of Project Element 3.4 (McElroy and others).

These coordinated research efforts involving members of multiple existing projects will culminate in new interdisciplinary geospatial analyses in 2017, centered around a workshop, and will be built upon the following three project elements with the following 7 objectives:

***Element #1 (2015) –** has one objective*

1. Complete Humminbird® Sidescan Sonar Mapping Methods - in 2015, for determining changes in the areal extents of sand and gravel bed surface sediment types using low-cost, easy-to-use sidescan sonar technology, where drifting benthic organisms and spawning trout are monitored in Glen and Marble Canyon study segments,

***Element #2 (2015-16) –** has five objectives*

1. Use of Glen Canyon Channel Map to Support Aquatic Modeling Research - Project 3 element 3.2, channel topographic and bed-sediment type map for Glen Canyon, data collected in 2015 (see Grams and others), will be used with flow model (Project 5) to support primary production model, and assessment of channel margins and shorelines in task 3, below,
2. Document Geometry of Glen Canyon Channel Margins and Grain Size – in 2015-16, the proportion of low-angle channel margins (less than 11 degree slopes, after Korman and others, 2005) known to be used by juvenile trout in Glen Canyon,
3. Document Geometry of Marble and eastern Grand Canyon Channel Margins – using existing channel data from previously mapped segments of Marble and Eastern Grand Canyon within NO study sites, we will estimate the proportion of low-angle channel margins (less than 11 degrees) for comparison with results from task #3 above,
4. Determining the Time-Varied Proportion of Sand and Gravel in Deeper Channel – through use of new and existing channel-map data, we will estimate the time-varied spatial distributions (2012-16) of sand and gravel areas on the Colorado River bed surface that may support rainbow trout spawning in NO study sites 1 - 4b,
5. Determining Time-Varied Proportion of Channel Margin Types in NO Study Sites – to assess possible influences on fish catch rates in NO study reaches #1 - 4b between 2012-16, associated with changing shoreline and near-shore sand deposits (low elevation eddy and lower channel sandbars) that may result from tributary sand inputs combined with high flow dam operations.

***Element #3 (2017) –** has one objective*

1. Synthetic Analysis of Rainbow Trout Catch and Physical Data – Integrating, in 2017, five years of physical (segment-scale channel geometry, changes in areal bed surface sand coverage, and variations in flow patterns, total suspended sediment flux and water temperature) and biological (the aquatic foodbase, in terms of invertebrate drift) and rainbow trout responses; analyses developed through an integration workshop approach.

Downstream of GCD, QW, suspended-sediment transport and sandbars (Project 2 and 3) are already monitored by the GCMRC in support of several GCDAMP information needs. However, recent data and advances in understanding about how specific dam operations can affect aquatic resources, such as benthic invertebrates and rainbow trout that are linked to the river bed and channel margins (Kennedy and others, 2013a; 2013b; Cross and others, 2012; Korman and others, 2011;12) suggest that there is a greater need to evaluate changes in QW and physical characteristics of the river channel through collaborative analyses between physical and aquatic scientists. The integrated goal of this proposed interdisciplinary effort is to increase understanding about how specific dam operations under drier hydrology from global warming may directly or indirectly influence fish distribution, abundance tied to early life history responses to changes in QW, use of changing channel margins (more or less sandbars and/or riparian vegetation) and bed-sediment type up and downstream of the Paria River confluence.

C. Background

Despite its 1996 reoperation (USDOI, 1995; 1996), GCD releases can still vary quite widely over hourly-to-decadal time scales in response to variations in upper basin hydrology and Lake Powell storage. Relative to pre-regulation, average daily flow is now much higher, but much less steady, while annual peaks are only a fraction of previous floods that occurred in Grand Canyon prior to dam closure (Topping and others, 2003). Hourly patterns of GCD water release, termed *Modified Low Fluctuating Flows* (MLFF) vary with monthly and annual water release volumes that are governed by upper Colorado River basin hydrology, water transfer agreements, and hydropower electrical energy demands. As a result, these factors can all directly influence inundation of channel margins used by aquatic organisms, as well as flow velocities and shear stresses along the river bed below the dam. Downstream variation in channel geometry within and between Glen, Marble and eastern Grand Canyon river segments means that abiotic and biotic resources can be affected differently by changes in hourly, daily, seasonal or annual patterns of releases (see figure 3 of Alvarez and Schmeeckle, 2012). In addition, suspended-sediment transport, spatial segregation of fine and coarse sediments of the river bed that affects channel geomorphology, and QW below the dam, including water temperature and turbidity, all vary longitudinally throughout GCNRA and GCNP. Spatial gradients in these quantities are known to change through time in response tributary sediment inputs, water storage in Lake Powell, and dam operations (Gloss and others, 2005). Perhaps the largest influence of GCD operations on downstream aquatic organisms has been that of thermal “pollution” – meaning generally colder dam releases which have a severely diminished range in seasonal water temperature (Olden and Naiman, 2010) that resulted from filling of Lake Powell by 1980.

During the last two years, GCDAMP stakeholders have expressed interest in better understanding whether or not dam releases below 8,000 ft^3/s might negatively influence the foodbase and recreational rainbow trout fishery in Glen Canyon. In support of foodbase research tied to this question, the combined outcomes of Projects 3 and 10 will provide aquatic foodbase researchers with channel geometry, channel-bed sediment type, and bed grain-size at Four-Mile Bar and other low-angle shoreline areas within Glen Canyon; information required to evaluate early life-stage survival of invertebrates and low-flow influences on the foodbase (*see projects 5.1 and 5.2*). Shallow nearshore channel margin areas as well as deeper parts of the channel with coarse-grained sediments (gravel) are known to be important substrates that support primary production and aquatic food for tailwater fish, as well as areas required for rainbow trout spawning and juvenile trout rearing. Better quantification and understanding about how varying dam releases alter channel-bed sediment types (sand and gravel), and inundate channel margins used by juvenile rainbow trout throughout Glen Canyon requires more detailed channel map data than currently exists in the GCD tailwater if understanding about how dam operations influence trout dynamics is to be improved.

Implementation of a decade-long High Flow Experiment (HFE) Protocol in 2012, now potentially allows HFEs to occur 1 to 2 times annually following Paria River floods that supply sufficient new sand to the CRe below Glen Canyon. The potential increasing frequency of these high-flow operations, in combination with other higher releases to manage water storage in Lakes Powell and Mead, provides a unique chance for scientists and managers to conduct integrated studies of the influence of dam operations on both sediment, fish and the foodbase during 2015-17 research and monitoring. Nearly all of the data required for ecological assessments are already being collected from various monitoring projects, and this project aims at integrating these diverse data through collaborative analyses. Information from integrated studies on how specific dam operations influence the river's bed-sediment type, inundation of channel margins used by fish, and other aquatic organisms is needed by members of the GCDAMP, but will also inform resource managers working to complete an ongoing environmental impact statement required to implement a 20-year Long Term Experimental Management Plan (LTEMP) for operating Glen Canyon Dam (see: http://ltempeis.anl.gov/).

C.1. Scientific Background

The GCD tailwater is commonly referred to by recreationists, managers and scientists as "The Lees Ferry reach" and contains a popular and highly valued recreational rainbow trout fishery within the remaining ~15-mile long segment of Glen Canyon, extending from the dam to the confluence of the Paria and Colorado Rivers (Korman and others, 2010). Glen Canyon has generally been considered to be the main source of rainbow trout found in GCNP, and is where most of the CRe's limited aquatic food is produced (mainly composed of drifting benthic invertebrates; Kennedy and others, 2013a). Owing to the facts that Lake Powell traps about 94% of the river's upstream fine sediment supply, and Paria River flows are of limited duration and highly variable, winnowing of fine sediments on the bed of the river below Glen Canyon occurs nearly continuously under most dam operations. Because sand and finer particles are efficiently transported downstream by higher MLFF releases (greater than about 9,000 ft^3/s; Topping and others, 2000) in the main channel between Paria River sediment deliveries, long periods may occur when the tailwater, and its discontinuity distance created by the dam may extend below the Paria River confluence. Sediment researchers have extensively studied the influence of dam operations on sediment transport, and bed winnowing as these physical processes relate to fine sediment resources in GCNP (Grams and others, 2013; Schmidt and Grams, 2011a; 2011b; Wright and others, 2010; Grams and others, 2007; Grams and Wilcock, 2007; Rubin and others, 2002; Topping and others, 2000;). However, the process of bed winnowing with respect to fine sediment below the dam has not been fully evaluated as an integrated part of aquatic resource monitoring and research projects, particularly those focused on rainbow trout and the food base.

Glen Canyon

Although the CRe is impounded by a single large dam, Kennedy and others have described the GCD tailwater as being highly impaired on the basis of the river's low diversity of aquatic invertebrates, and complete lack of three key indicator invertebrate taxa (written commun., US Geological Survey, 2013). At full pool, the dam impounds about 4 years of upper Colorado River basin runoff in Lake Powell; resulting in release temperatures more like those found in alpine river settings. The impounded river below the reservoir consists of several different "rivers" or segments, each with their own unique characteristics; the first being the remaining segment of Glen Canyon not inundated by Lake Powell. Glen Canyon is a meandering segment of the Colorado River incised into Navajo Sandstone with only a few ephemeral tributaries which rarely flow and contribute very little sand to the channel below the dam. An exception to this occurred in August 2013, when two large floods in Waterholes Canyon, a tributary about 3 miles upstream of Lees Ferry, added volumes of gravel and fine sediment to lower Glen Canyon at about the mid-point of NO study reach 1 (lower 1/3 of Glen Canyon). Although details about these floods are not yet available, the sediment inputs appear to have altered the river's channel-bed and channel margin sediment type immediately below this ephemeral tributary (preliminary observations, Yard, Korman and Melis, 2013). In winter 2013-14, NO researchers later reported declines in quarterly rainbow trout catch, perhaps in response to increased sand coverage of the gravel bed and channel margins (preliminary data, Korman and Yard, US Geological Survey, 2014). Juvenile trout are known to use interstitial pore spaces in gravel-bed settings as sheltering habitat during early life stages (Finstad and others 2007), and embeddedness of coarse particles by sand and finer sediment may affect use and survival of juvenile fish. The Waterholes Canyon flooding was an important motivating influence for this project, as well as other questions recently raised by recreational anglers about possible influences of lower-flow dam operations on the trout fishery during 2014 (the WY 2014 7.48 maf minimum release volume has been the lowest since 1964). Recent evaluation of existing Glen Canyon channel data associated with low-angle channel margins accessed by juvenile trout (figure 2-upper panels; preliminary data, Melis and Grams, US Geological Survey, 2014), indicates that dam releases result in very different types of shoreline changes as flow increases between the dam and Lees Ferry. Use of low-angle near shore channel margins by juvenile trout is therefore likely to be quite variable throughout Glen Canyon under diurnal fluctuating releases associated with hydropeaking operations. Trout researchers have suggested that knowing more about how dam releases inundate low-angle channel margins used by trout would advance understanding about how various stable or fluctuating flows influence early life survival of rainbow trout. Figure 2 (lower) shows the variability in deep versus shallow areas of Glen Canyon, and most low-angle channel margins are located near the shallower channel sections, such as Four Mile Bar (RM -3.9). Additional details on Glen Canyon channel change history since closure of GCD can be found in the Project 3, element 3.2 (Grams and others, above).

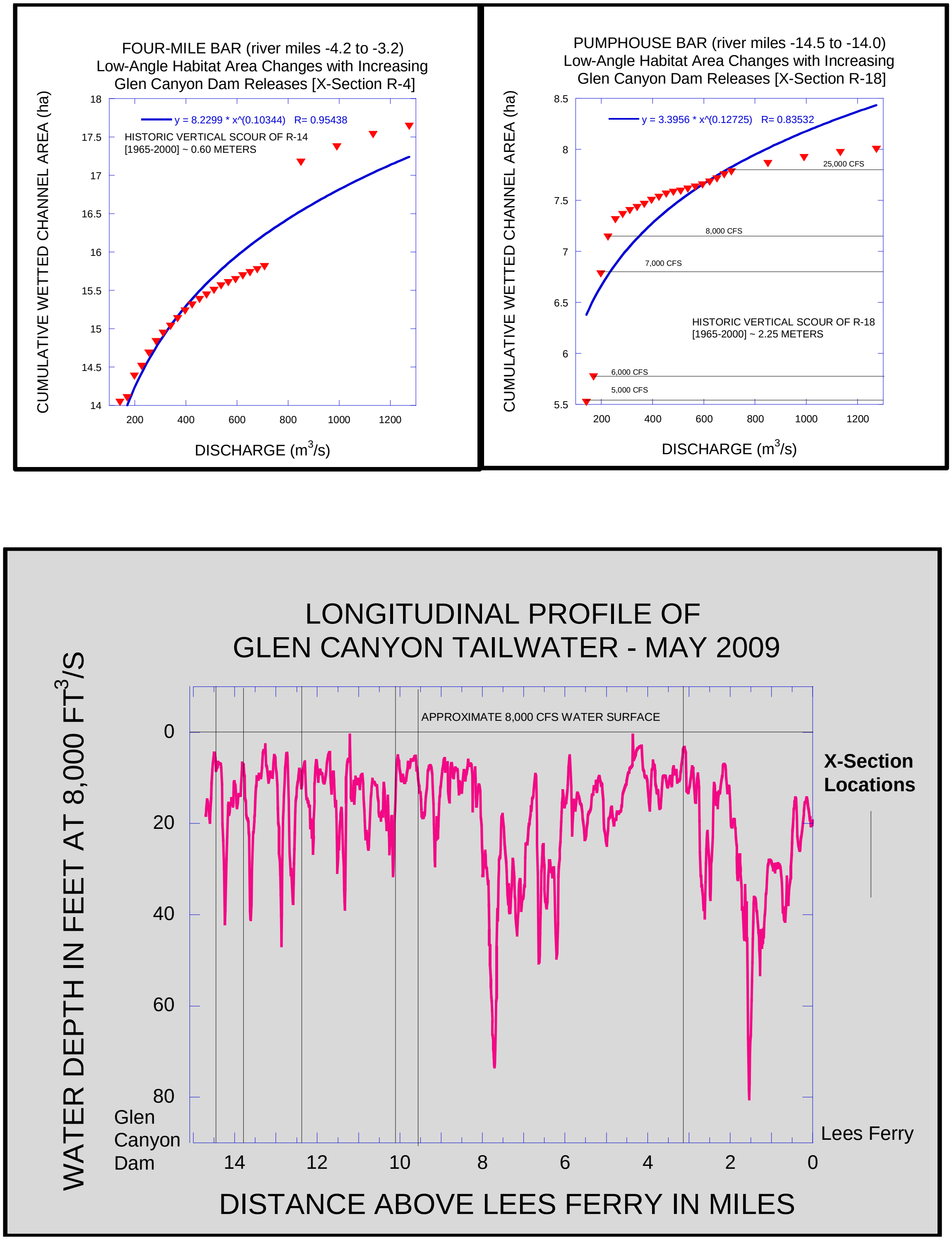

Figure 2. Top panels - two examples of hypsometric profiles, or channel-margin inundation curves derived from 2 dimensional cross sections located adjacent to low-angle gravel bars in Glen Canyon; (**upper left**) Four-Mile, and (**upper right**) Fourteen-Mile Bars, (located 4 and 14 miles upstream from Lees Ferry, repsectively). Though not derived from modelled flows, or even thought to be fully representative of river stage and inundation across the entirety of either of these bars, the examples demonstrate the range of variability in gravel bar area river shorelines at low-angle channel margins between the dam and Lees Ferry for dam releases ranging from the lowest to the highest flows that typically occur under MLFF operations (preliminary data, Melis, Gushue and Grams, U.S. Geological Survey, 2014). **Lower panel** – longitudinal depth profile of the bed of the CRe (measured at a flow of 8,000 ft^3/s) between Glen Canyon Dam and Lees Ferry in late May

2009, (with large vertical exaggeration) showing the high variability in flow depth in the post-regulated era (preliminary data, Melis, Andrews and Kennedy, U.S. Geological Survey, 2009).

As Lake Powell filled during the 1970s, Glen Canyon was further transformed from its setting as a desert river to one with near-perfect conditions for establishment of a highly prized GCNRA rainbow trout sport fishery through annual stocking that continued into the 1990s. Between 1986 and 2002, dam releases were cold owing to hypolimnetic reservoir releases from Lake Powell through the GCD hydropower plant, with little annually variation. The river in Glen Canyon in that era was about 3-8º C colder than optimal temperatures needed by rainbow trout for spawning, egg incubation and growth (Valdez and Speas, 2007). By 1980 GCD and Lake Powell had even created a "thermal" discontinuity in the Colorado River with respect to introduced trout. A similar issue was recognized on the Green River below Flaming Gorge Dam, but alteration of the thermal regime there was mitigated through construction and operation of a selective withdrawal structure to warm dam releases to manage the tailwater sport fishery (see figure 6 of Olden and Naiman, 2010).

Glen Canyon Dam Operations and Rainbow Trout

In keeping with the river continuum and serial discontinuity concepts, GCD releases from Lake Powell are virtually devoid of fine sediment most of the time, resulting in turbidity levels more typically found in a headwater mountain stream than in a desert river (Ward and Stanford, 1983). Hence, the channel bed remained armored from the 1965 releases, and Kondolf and others (1989) report that grain-size distributions of gravel in Glen Canyon were "adequate" for trout spawning when sampled in the mid-1980s. However, daily ranges in GCD releases associated with hydropeaking operations between 1965 and 1991, are believed to have limited natural rainbow trout reproduction in Glen Canyon (Maddux and others, 1987), and the fishery required annual stocking to be maintained as a recreational resource until after daily fluctuations became more limited in the 1990s. Despite channel scouring following dam closure in 1963, many areas of the river in Glen Canyon remain relatively shallow, particularly at lower MLFF dam releases of 8,000 ft^3/s or below (figure 2-lower panel). Trout spawning areas in Glen Canyon are often located along shorelines and channel margins, particularly along point bars, such as the Four Mile Bar, but redds are also observed in the deeper parts of the river channel (Korman and others, 2005). Experimental daily fluctuating flows ranging from 5,000 to 20,000 ft^3/s in January through March 2003-5, were intended to lure spawning trout onto higher parts of gravel bars; areas where lower daily flows would then desiccate eggs in redds down to 5,000 ft^3/s and hence limit trout survival. However 5,000 ft^3/s flows were found to be insufficient to reduce the Glen Canyon trout population owing to compensatory survival of fry that emerged from deeper redds in the channel (Korman and others, 2011; Korman and Melis, 2011).

Following reoperation of the dam in 1996, MLFF releases were observed to support natural reproduction of rainbow trout and allowed for the fishery to become self-sustaining (Walters and others, 2000). Recent channel surveys (preliminary data, Grams and others, US Geological Survey, 2014) and 1998 resurvey of Marble Canyon cross sections, plus suspended-sediment transport monitoring in channel segments downstream of Glen Canyon (preliminary channel data from the late 1990s, and WY 2011 data, Topping and others, US Geological Survey) suggest that similar channel-bed adjustments may have continued downstream of Glen Canyon since dam closure in 1963. What might be the implications of channel-bed sediment winnowing in Marble Canyon (coarsening of bed grain size and reduction of bed coverage by fine sediment) if the grain size of bed sediments evolve there in ways similar to those observed in 1965 above Lees Ferry?

Our first hypothesis follows after this question: "*Dam operations that support trout*"

Hypothesis - 1: Operations of Glen Canyon Dam result in progressive winnowing of the channel-bed to the extent that coarsened bed sediments of the main channel, combined with ongoing tributary inputs of gravel, and QW conditions, increasingly support life history requirements of nonnative rainbow trout within and downstream of Glen Canyon.

We suggest that river managers consider the possibility that such combined influences of GCD operations may, at least in part, explain the recently emerging 2013-14 presence of abundant age-0 fish caught in lower Marble and eastern Grand Canyons (figure 3). To date, Korman and Yard report that preliminary NO catch data from NO reach #2 (RM16 to RM20) of upper Marble Canyon through April 2014, have yet to include juvenile trout, but do contain abundant adult rainbow trout. One possibility for explaining this might be the upstream influence of 2012-13 Paria River sand inputs and resulting sand coverage of the deeper channel bed upstream of mid-Marble Canyon, among several other possible reasons.

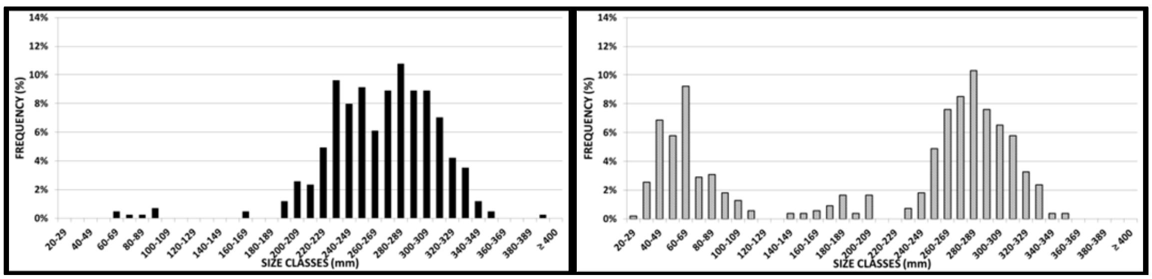

Figure 3. Length-frequency rainbow trout catch data collected by NO project from reach 4b (river miles 62-64 below the LCR confluence). Left – July 2012 catch includes mostly adults. Right – July 2013 catch includes abundant juveniles (preliminary data, Korman and Yard, US Geological Survey, 2013). Similar emerging patterns to the July 2013 data have also been detected in 2014 within NO reaches 3 (mid Marble Canyon) and 4a (lower Marble Canyon).

Following the March 2008 HFE, Korman and others (2011) report that rainbow trout survival and recruitment in Glen Canyon was above average in 2008-9. This enhanced fish production is thought to have, in part, been the result of flood disturbance of the channel bed in Glen Canyon; a process that resulted in reduced production of benthic invertebrates overall, but with elevated production of a couple of benthic taxa that were important dietary items for juvenile trout fry after their emergence from gravel redds (Cross and others, 2012). Korman and others (2012) also report that other experimental and management flow operations from GCD since 2008, that have been associated with enhanced rainbow trout production on the basis of monitoring data and modelling simulations (figure 4).

High-flow dam releases since GCD was experimentally re-operated to MLFF rules in 1996, such as the March 2008 HFE, indicate that such flows are large enough to "cleanse" the channel bed below the dam of finer sediment and other debris that clog interstitial pore spaces used by trout and benthic invertebrates (Cross and others, 2012; see table 1 of Melis and others, 2012; Korman and others, 2011).

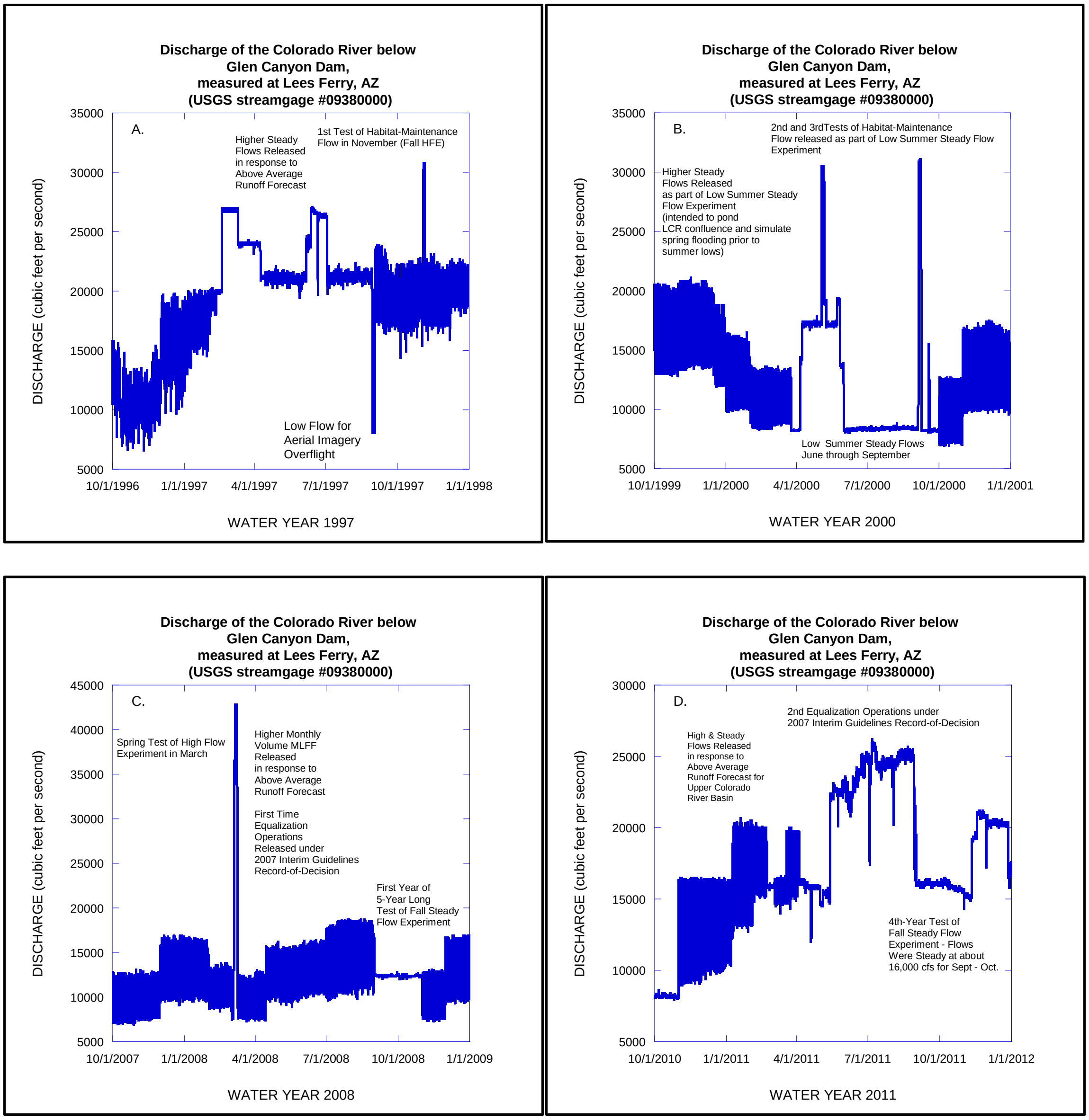

Figure 4. Flow hydrographs for Colorado River measured at Lees Ferry, AZ (USGS streamgage #09380000) – these show Glen Canyon Dam releases in water years during which Korman and others (2012) modeled above-average rainbow trout survival/recruitment: (a) 1997, (b) 2000, (c) 2008, (d) 2011. Each of these hydrographs contains annual release volumes greater than the minimum required water transfer from the Upper to Lower Colorado River Basin, and have similarities in that each year had periods from winter through summer and fall in which river flows were higher and steadier than would otherwise have likely occurred during minimum-volume release years after 1996 (8.23 million acre feet), without reservoir equalization between Lakes Powell and Mead, or experimental flows (2001-02, and 2006-07). Since the Glen Canyon Dam EIS was completed in 1995, experimental flows of one type or another have occurred in: 1996-97, 2000, 2003-05 and 2008-13. Water Years 1998-99, were the only years of MLFF operations associated with larger than minimum annual release volumes, but no experimental flow treatments other than MLFF.

The four annual hydrographs shown in figure 4, each have common elements of higher flows in late winter through spring, as well as a component of increased daily flow stability during seasons in which trout early life-stage survival are known to respond positively, at least within Glen Canyon (Korman and others, 2005; 2011; 2012). In 2011, the largest estimated trout recruitment year to date, dam operations were managed most of the year to achieve required “equalization” water transfer from Lakes Powell to Mead, but experimental steady flows in

September-October 2011, were also released at about 16,000 ft^3/s. The Water Year 2011 hydrograph was characterized by relatively high and stable flows relative to most MLFF releases that had occurred from about 2001, up to that time. Korman and others (2012) conclude that high flows in spring, and steady flows after trout fry emerge from redds, appear to support elevated juvenile trout survival in Glen Canyon. Perhaps similar dam releases might also benefit rainbow trout in Marble and eastern Grand Canyons. However, to date early life-stage survival studies including redds inventory surveys, such as those conducted by Korman and others in 2003-6, (Korman and others, 2005), have only been conducted within Glen Canyon.

A key uncertainty recently identified by aquatic biologists about HFEs is whether fall-timed high releases would also disturb the channel bed in ways that increase rainbow trout populations in Glen Canyon, or result in more abundant trout in GCNP (Kennedy and Ralston, 2011)?

Our second hypothesis follows after this question: "*High-flow frequency and timing*"

Hypothesis - 2: Increasing frequency of higher and more seasonally varied thermal releases from Glen Canyon Dam increases rainbow trout production in the GCD tailwater regardless of seasonal timing, but this response is also spatially controlled by the abundance and distribution of fish and available food items in Glen, Marble and eastern Grand Canyons, as well as the timing, frequency and magnitude of Paria River floods.

During recent periods from 2003-13, when Lake Powell storage has been reduced, available QW data from lower Marble Canyon suggest that the thermal discontinuity distance below GCD, at least with respect to rainbow trout life history requirements, has likely retreated upstream of the Little Colorado River into Marble Canyon. Bioenergetic needs and muscle recover times of rainbow trout have been shown by Kieffer and others (1994) to be sensitive to increased temperatures. In addition, Robinson and Uehlinger (2008) also report that increased frequency of artificial flood disturbance over several years of experimental releases in the River Spol, and alpine river with somewhat similar thermal and benthic invertebrate characteristics as the CRe, led to gradual shifts in the benthos associated with improvements in a brown trout fishery below a hydroelectric dam. Owing to relatively more frequent high releases from GCD since 2008, more seasonally variable water temperatures in lower Marble Canyon combined with periods of low turbidity, and relatively shallow river depths in spring seasons of 2012-13, we therefore propose to integrate QW data with channel-bed sediment and fish catch data in evaluating the above hypotheses.

Marble and Eastern Grand Canyons

Below Glen Canyon, the Colorado River through Marble Canyon descends through harder Paleozoic lithologies that contribute very coarse sediments to the main channel from small, ephemeral tributaries during infrequent hill slope failures that result in debris flows. These bouldery debris flow deposits create a series of pools and drops where rapids are formed below tributary channel constrictions. The Marble Canyon segment is most clearly distinguished from Glen Canyon by relative absence of frequent point bars, but appearance of numerous debris fan-eddy complexes. These landforms are river reworked lag deposits accumulated from repeated debris flows over time (Melis and others, 1995), that locally constrict the river's channel and create recirculating flow zones that are effective traps for sand and finer sediment transported in suspension (Schmidt and Rubin, 1995).

Owing to Glen Canyon Dam and Lake Powell, only about 6% of the CRe's former sand supply is still delivered to the upstream boundary of GCNP in Marble Canyon by the Paria River just below Lees Ferry (Topping and others, 2000). This is the primary sand supply available to rebuild and maintain sandbars in the eastern third of park when high flows are released that can move sand from the river bed and redeposit it along the channel margins (Schmidt and Grams, 2011b). Currently, an experimental 10-year protocol of HFE releases from the dam is ongoing through 2020, in which each experimental release occurs following tributary sand inputs from the Paria River. Because Paria River floods that enrich the CRe with sand and finer sediment are relatively infrequent, but releases from the dam are nearly always devoid of fine sediments, winnowing of channel-bed sand in Marble Canyon occurs most of the time. During experimental high flows intended to rebuild sandbars within eddies, bed winnowing is in-fact a required process, whereby new sand in the lower areas of the river channel are suspended and carried into near shore areas along channel margins and re-deposited at higher elevations.

The upper Tapeats Sandstone gorge of GCNP is bisected 61 miles below Lees Ferry by the Little Colorado River (LCR) at its confluence with the Colorado River. Eastern Grand Canyon begins at this point. The LCR is the natal origin source area for the largest population of endangered humpback chub, is a second major source of sand to the main channel, and is also one of three potential source areas for exotic fish introductions to the Colorado River in Grand Canyon. The LCR is also a second significant downstream source of silt/clay loads to the main channel below the dam. Turbidity values measured 26 miles downstream of the LCR confluence are typically elevated above levels resulting from Paria River fines input to Marble Canyon. On the basis of both water temperature and downstream turbidity, one might reasonably conclude that the LCR is the downstream boundary of the GCD discontinuity distance with respect to nonnative trout and the CRe's foodbase, but not perhaps relative to native fish in terms of either turbidity or temperature.

Recent Lower Marble Canyon Sediment Monitoring Data

Besides site-to-site variation in how a given flow from the dam might inundate specific channel-margin areas used by rainbow trout, it's also important to recognize that above-average dam operations in 2011, were also very effective at exporting a large volume of the highly limited sand supply in Marble Canyon downstream, as reported by Topping (U.S. Geological Survey, written commun., January 2012, as the annual volume released from the dam was about 50% greater (12.5 maf than prior minimum annual releases of 8.23 maf). The estimated sand budget for the lower 30 miles of Marble Canyon between May 2009 and 2012, suggests a sand deficit within measurement uncertainties; one that appears to have mostly resulted from 2011 operations (figure 5-left).

One possible influence of sand export from Marble Canyon might be that sediment on the river bed becomes coarser grained as finer particles (sand and finer) are winnowed (Rubin and others, 2002). Topping and others (2003) report that re-operation of GCD in the 1990s actually reduced the percentage of time that sand inputs from the Paria River can accumulate on the river bed (figure 5-right) as a result of reduction in the lower flows that commonly occurred from 1965 until late 1991. Ongoing annual inputs of sediment coarser than sand from smaller ephemeral tributaries in Marble Canyon (Webb and others, 2000), also means that gravel supplied to the bed of the Colorado River below Lees Ferry could also be potentially augmenting trout spawning areas of the deeper bed as sand is exported downstream under most dam releases. Preliminary results from channel mapping (Project 3, Grams and others, US Geological Survey, 2014) conducted over a three year period from 2009 to 2012 in lower Marble Canyon also support the downward trending sand budget over the same period (figure 5-left). The repeat channel surveys also reveal that the majority of sand lost from the 30-mile long river segment was evacuated from the deeper parts of the channel bed outside of eddies where most sandbars are found. An example of bed map imagery is shown in figure 15 of Project element 3.4 (above).

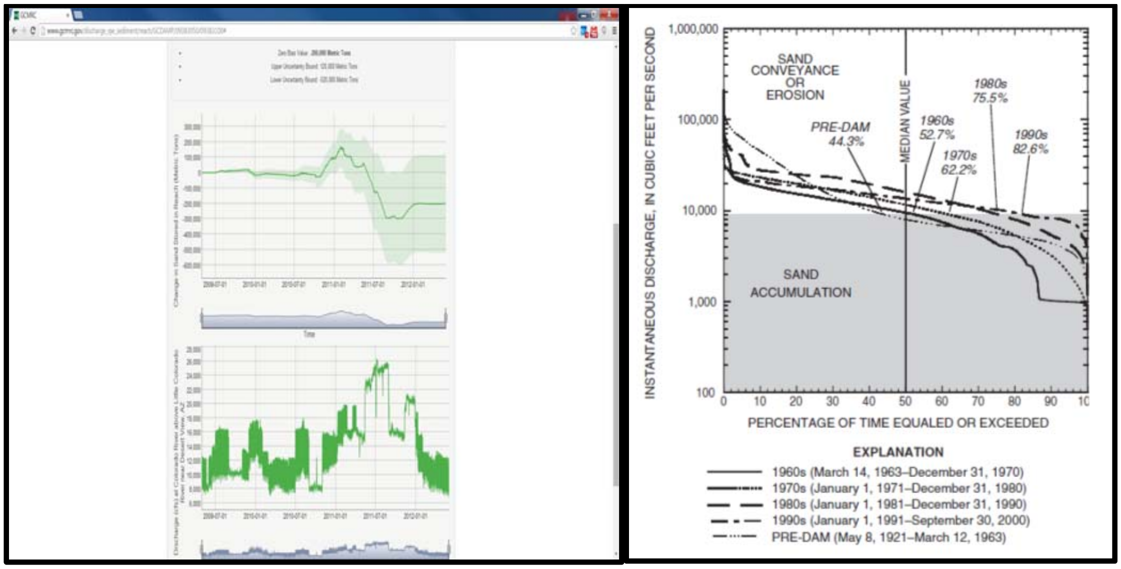

Figure 5. Left - cumulative sand budget for Lower Marble Canyon (river miles 30-61) from May 2009 to June 2012, and discharge at the Colorado River above the Little Colorado River near Desert View, AZ. Although the budget over this 3-year period is still technically indeterminate within the uncertainty bounds, it more clearly suggests sand mass export from Lower Marble Canyon (GCMRC preliminary sand budget, 2014; www.gcmrc.gov), and the downward trend in sand storage supports topographic channel-bed monitoring of the segment from May 2009 to May 2012, that indicates about 0.47(+/-0.15) Tg of sand were eroded from the main channel of Lower Marble Canyon in the period between the mapping surveys (Grams and others, preliminary data, USGS 2014). **Right** - Flow-duration curves for the Colorado River at Lees Ferry from each of the four post-dam decades and the entire pre-dam period. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons. The percentages of time when these discharges were exceeded during each period are indicated in italics (from Topping and others, 2003). This trend suggests that MLFF has probably been effective at keeping the channel bed in lower Marble Canyon highly winnowed with respect to sand and finer sediments, and implementation of the 2012-20 HFE protocol, allowing annual clear water floods annually in the fall might also be providing areas of gravel exposure and lower water turbidity during the December through June periods; seasons when rainbow trout are typically known to spawn below Glen Canyon Dam.

Recent Lower Marble Canyon Water Quality Data

Korman and others (2012) report that high and steady releases from the dam throughout much of Water Year 2011, and the earlier spring 2008 HFE both resulted in above average rainbow trout survival and recruitment in Glen Canyon. Fish monitoring data in Marble and eastern Grand Canyons after 2010, indicate that rainbow trout abundance increased below Lees Ferry, but most trout were assumed to have derived from Glen Canyon source area. As already mentioned, recent trout catch data from the NO project in July 2013, as well as January and April 2014, suggest that rainbow trout reproduction has been occurring in either lower Marble or eastern Grand Canyons (figure 3). The most recent spring 2014, preliminary catch data also suggest possible spawning further upstream in mid-Marble Canyon as well. (preliminary data, Korman and Yard, US Geological Survey, 2014). One possible explanation for these observations is the presence of more trout below Lees Ferry since 2011, but other information likely also must be considered to explain downstream abundance of juvenile trout.

Recent (2006-13) QW data collected from the Colorado River 61 miles downstream of Glen Canyon, provide insight about the July 2013 juvenile rainbow trout catch data collected by NO researchers in their most downstream study site (NO reach 4b) just below the confluence of the Little Colorado River (figure 3). The median water temperature of the Colorado River in lower Marble Canyon during the December through May period (months when rainbow trout are observed to spawn in Glen Canyon) of Water Year (WY) 2013, was only slightly above the optimal temperature of 10º C for rainbow trout spawning and egg incubation (figure 5-left; Valdez and Speas, 2007). Bioenergetic and food availability must also be considered relative to temperature influences and trout metabolism (Elliott, 1984; Kieffer and others, 1994), and Kennedy and others (2013a) report aquatic food to be a limiting factor for fish in the CRe.

As part of a risk assessment study of thermal conditions and fish below GCD, Valdez and Speas (preliminary data, R. Valdez and D. Speas, 2007, written commun., Bureau of Reclamation) estimated "assessment scores" for native and nonnative species found in GCNRA and GCNP, under two simulated thermal regimes for operation of GCD; with and without a selective withdrawal structure (SWS) added to the project's hydropower plant intakes. The purpose of the previously proposed SWS, is to mitigate thermal pollution from GCD, and manage for warmer water temperature releases downstream; the aim being to increase juvenile native fish survival, including humpback chub. Scores estimated for rainbow trout under the SWS simulations in both Glen and Marble Canyon suggest that this nonnative species is likely to benefit most from the relatively small increases in downstream water temperatures when a 2-unit SWS operation, with brown trout scoring second highest (preliminary data, R. Valdez and D. Speas, 2007, written commun., Bureau of Reclamation). Although an SWS is no longer being proposed for operation at the GCD, reduced storage in Lake Powell since about 2001, has resulted in downstream water temperatures that trend very close to those estimated from the SWS 2-unit simulations. In the late 1970s, Flaming Gorge Dam on the Green River was retrofitted with an SWS, and has been operated successfully, but mostly to increase downstream water temperatures to benefit nonnative sport fish, including rainbow trout (see figure 6 of Olden and Naiman, 2010).

Following sustained high releases from Glen Canyon Dam in the latter half of WY 2011, and the November 2012 HFE, the median value of main channel turbidity in lower Marble Canyon from December 2012 through May 2013,was very low (figure 5-right). On the basis of what is known about the life-history requirements of rainbow trout (Valdez and Speas, 2007; Korman and others, 2011), water quality in lower Marble Canyon was similar during winter through spring 2012-13, to conditions found upstream in Glen Canyon. However, many other factors might limit or promote trout spawning, egg survival and recruitment in lower Marble Canyon. Korman and Melis (2011) have suggested that careful and consistent monitoring of rainbow trout and factors associated with their survival and recruitment, including HFEs, is required to inform managers about GCD operating strategies aimed at co-management of native and nonnative fish below the dam.

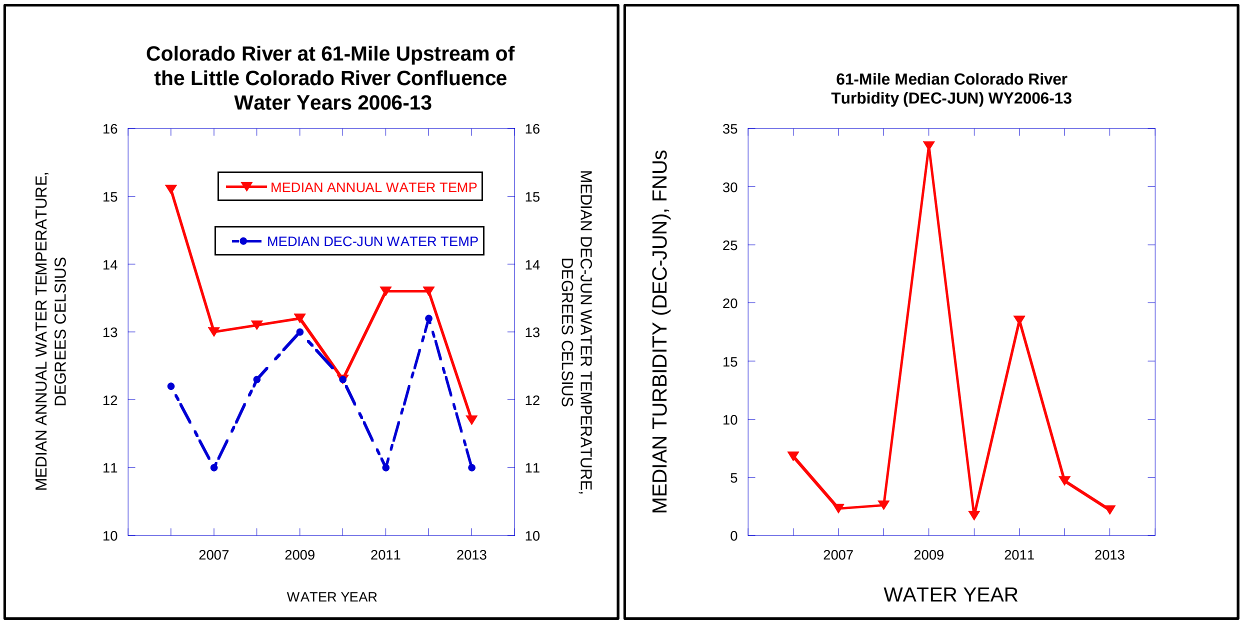

Figure 6. Left - median annual and (DEC through JUN) water temperatures of the Colorado River measured at river mile 61 in lower Marble Canyon for water years 2006-13 (NO reach 4a). December through June periods have tended to be colder than the annual median water temperature and contrast the most during Water Year 2011, when 12.5 million acre feet (MAF) of water were released from Glen Canyon Dam to equalize water storage between Lakes Powell and Mead. During the following Water Year 2012, by contrast, water temperatures were relatively warmer upstream of the Little Colorado River (NO study reach 4a) and about 2º C warmer than in 2011, during months when rainbow trout are known to spawn upstream in Glen Canyon. Both colder median annual and winter-through-spring water temperatures occurred in Water Year 2013, prior to preliminary juvenile rainbow trout catch data (July 2013) suggesting localized trout production in lower Marble Canyon. It is not presently clear how water temperatures, turbidity levels or channel-bed sediment types might influence aquatic food production and potential for rainbow trout spawning and recruitment below Glen Canyon, but monitoring has shown increased abundance of trout near the Little Colorado River since about 2011 (W. Pine, written commun. Univ. of Florida, 2012, and Korman and Yard, preliminary data, Ecometric Research and USGS, 2014). **Right** - recent levels of median turbidity (DEC through JUN) measured at river mile 61 in lower Marble Canyon for water years 2006-13. The winter through spring seasons shown follow the warm-season (JUL – OCT) when tributary fine-sediment inputs typically enter Marble Canyon from the Paria River and other lesser drainages upstream of the Little Colorado River. Rainbow trout studies in Glen Canyon suggest that fall through winter and into spring is the main period for spawning in the 15-mile long tailwater below Glen Canyon Dam. It is not clear if and to what degree both lower turbidity and channel-bed sediment types (presence of gravel suitable for redds) during 2012-13 in lower Marble Canyon might have contributed to July 2013 to April 2014, preliminary juvenile catch data suggesting localized trout production in NO study reaches 3 and 4a, located between 37 and 61 mile and just upstream of the LCR confluence with the main Colorado River.

Drift samples are also collected as an ongoing part of rainbow trout research within all NO study sites during seasonal fish monitoring to evaluate trout diets. At present, those data are not yet available, but increasing water depth has been identified by Yard (2003) as an attenuating factor in solar insolation reaching the river bed under low turbidity, and may therefore also limit primary production. It is possible that higher rainbow trout abundance in lower Marble Canyon observed after 2011, combined with more optimal water temperatures for spawning and egg incubation in winter, plus low turbidity and warming in late spring and summer may have promoted aquatic food availability and trout growth in spring 2013. Such influences may partially explain large numbers of juvenile trout captured recently by NO researchers below Lees Ferry. But what about conditions of the channel bed with respect to suitable spawning gravels? Channel-bed sediment data that might shed light on this question have been collected by Project 3 (channel and sandbar mapping) scientists in May of 2009 and 12, as part of sand storage monitoring throughout lower Marble Canyon, but have not yet been evaluated relative to trout monitoring data collected by NO researchers. Similarly, the river segment just below the LCR confluence (NO study site 4b) was also mapped by sediment researchers in May 2011 and 14, as part of eastern Grand Canyon sandbar monitoring (Project 3, Grams and others). We propose that an integrated evaluation of these valuable physical data sets with fish data is needed to address new and emerging ecological questions (figure 1). We believe that this research must now be undertaken to further inform managers about how dam operations may be influencing aquatic resources through downstream changes in physical characteristics of the GCD tailwater.

"STAGE" SET FOR A THIRD HYPOTHESIS

Korman and others (2012) also report that high and steady flows in spring through summer, may also provide trout fry that emerge from gravel redds access to expanded near-shore areas that are hypothesized to enhance juvenile survival. One of these areas, Four Mile Bar in Glen Canyon, was observed by fisheries scientists (Korman and Avery, 2011) to be shallow, warm and vegetated with extremely abundant numbers of juvenile rainbow trout in summer 2011 when dam releases were steady at about 25,000 ft^3/s. This is one hypothesis for why the 2011 rainbow trout cohort likely exceeded the 2008 HFE response. Owing to geomorphic variations in the Glen Canyon channel width, and non-uniform 1965 vertical channel scouring that transformed Glen Canyon gravel bars, we estimate that any given dam release will inundate the low-angle channel margins differently, and these are areas known to be used by juvenile trout in the Lees Ferry tailwater (Korman and others, 2011; figure 2-upper panels). How different are distributions of low-angle and steeper channel margins in Glen, Marble and eastern Grand Canyon NO study areas, and which of the low-angle channel-margin areas used by rainbow trout throughout these river segments are most sensitive to river inundation or dewatering in response to hourly varied GCD operations?

Our third hypothesis follows after this question: "*Flow variations and shoreline changes*"

Hypothesis - 3: Geomorphic differences of the Colorado River's channel geometry within NO reaches 1 & 4b, combined with behavior of flow and stage, result in varied channel margins, and these differences influence fish access to near shore areas in ways that limit the influence of how hourly changes in flow affect trout below GCD relative to their distribution, abundance, growth and survival of age-0 rainbow trout.

As such, experimental dam operations that have been recently discussed by GCDAMP stakeholders and LTEMP cooperators for managing rainbow trout abundance below the dam in Glen and Marble Canyons, may have limited downstream effectiveness on early life-stage survival of rainbow trout. Without proposed 2015 mapping by Project 3 (see description for element 3.2), developing more detailed hyposometric profiles (relationship showing area of channel margins covered by water over a range of river stages and dam releases using flow modeling methods) is only possible for Glen Canyon from Lees Ferry upstream to about Six-Mile Bar, where shoreline and channel bathymetry were previously obtained in 2004 and 2009. Upstream of Six-Mile Bar, full channel bathymetry has not been collected. In most of Glen Canyon only widely spaced cross sections exist (Grams and others, 2007), but most of them are not ideally located close to juvenile trout nursery channel-margin areas to be fully informative to NO or foodbase researchers (Projects 9 and 5). Further, without development of a flow model in Glen Canyon in 2015 (see project 5, Kennedy, Muehlbauer and Wright), shorelines can only be crudely estimated in low-angle channel margin areas using a few of the widely spaced, cross sections and associated rating curves. A two-dimensional flow model already exists for NO reach 4b, and we propose to use it for estimating shorelines along channel margins below the LCR confluence (RM62-RM64) where rainbow trout and juvenile humpback chub are intensively monitored) in this project. A meaningful comparison of shoreline sensitivity to dam operations between fish sampling sites in lower Glen Canyon (NO reach 1) and NO reach 4b (lower Marble Canyon), requires that flow modeling be possible upstream of Lees Ferry as well (see Project 5 elements).

Depending upon which of the several hypotheses regarding rainbow trout growth are supported by ongoing research (*see hypotheses associated with Project 9*), recruitment of juvenile trout tied to use of low-angle channel margins in late spring and summer seasons (Korman and others, 2011) might be experimentally managed throughout the GCD tailwater using flow treatments patterned over specific stage ranges and changing flow rates. Hence, design of future flow experiments to manage the trout population in Lees Ferry, might be informed using low-angle channel margin and shoreline maps in NO reaches 1 (lower Glen Canyon) and 4b (RM62 to RM64 of eastern Grand Canyon), as well as information resulting from combined analyses of fish catch data and shoreline mapping. This new project, in combination with Projects 2, 3, 5, 9, and also possibly 11, intends to collect additional data about physical channel-margin characteristics (Table 1) that will allow more detailed assessments and understanding about how specific experimental and management dam releases influence use of channel margins relative to life history strategies of rainbow trout in Glen, Marble and eastern Grand Canyons.

C.2. Management Background

At least eleven resources are described within four Desired Future Conditions (DFC) associated with adaptive management of Glen Canyon Dam. Three of them include: protection of native fish, particularly the humpback chub; maintaining a quality recreational rainbow trout fishery immediately below the dam in GCNRA, while also simultaneously controlling nonnative fish in GCNP, particularly trout; and conservation of fine sediment (rebuilding and maintenance of sandbars also valued as camping beaches). All three of these valued resources are described in two of the DFCs "Colorado River ecosystem" and "Recreation", but understanding by scientists and managers about how each of these resources is tied to dam operations can vary from well documented to highly uncertain (Gloss and others, 2005; Kennedy and Ralston, 2011). Responses of sandbars, fish and their prey items, to dam releases also vary widely in time and space over 400 km of the CRe. The other two DFCs include hydropower, and cultural resources.

An ecosystem approach to long-term monitoring was identified as a priority by the GCMRC at the time it was established in 1996. During past reviews of the GCMRC and the GCDAMP, integrating physical, biological monitoring efforts with focused interdisciplinary analyses of diverse, but interrelated data was identified as a critically needed strategy for improved understanding about how Glen Canyon Dam operations influence downstream resources:

> "As pointed out in previous National Research Council reviews (1987, 1996a), an ecosystem approach seeks an understanding of interrelationships among important physical, chemical, biological, and social processes." (Wescoat and others, 1999).

Further, the 1999 review panel suggested that "Short term research projects must be closely linked with the monitoring program." and that "Physical, biological, cultural, and socioeconomic measures should be co-located in space and time wherever and whenever practical." In their review of the biological program at that time, the panel's final report states that "Linkages between and among biological and various other resource categories remain poorly articulated. It is therefore critical that the Biological Resources Program be closely integrated within itself and that, at a minimum, the Biological Resources and Physical Resources programs be tightly interwoven; it is not yet apparent that either condition is satisfied." (Wescoat and others, 1999). Since then, many advances have been made in areas of the GCMRC's physical and biological monitoring programs. However, less progress has occurred in the area of interdisciplinary research using now abundant monitoring data for focused science integration to address management uncertainties; particularly, those relating sediment to the CRe's nonnative and native fisheries, and the river's food base.

Conceptual ecosystem modeling was also identified in the GCMRC's initial 5-year strategic science plan as a critical activity to help identify gaps in monitoring, linkages between resources and dam operations, as well as alternative "policy" experiments that might also be considered for adaptive management of the dam. Two phases of such modeling between 1998 and about 2011, focused mostly on the CRe's aquatic resources, but understanding about how certain dam operations influence fine sediment, exotic rainbow trout and elements of the river's food web has been greatly advanced through flow experimentation, such as HFEs mainly intended to rebuild sandbars using the highly limited remaining sand inputs below the dam.

Although conceptual ecosystem modeling is not currently an element of the science program to support the GCDAMP, the legacy of past modeling efforts strongly suggests that aquatic ecosystem linkages with physical characteristics of the river channel that support fish and foodbase resources of GCNRA and GCNP, are particularly important areas to focus integrated research on. This may be particularly true now that ongoing sediment, flow, QW, and aquatic monitoring projects are well established.

Perhaps one of the largest uncertainties facing GCDAMP resource managers, may be dam operating options to achieve sustainable co-management of both valued nonnative recreational and endemic native fisheries below Glen Canyon Dam in GCNRA and GCNP. Uncertainties about trout in GCNP and their interactions with humpback chub are at the center of this goal (Yard and others, 2011; Korman and others, 2011; Korman and Melis, 2011). Because nonnative species are not desired within GCNP, but rainbow trout are highly valued as a recreational resource within GCNRA, the challenge of co-managing these two fisheries has a strong longitudinal and geographical context relative to Glen Canyon Dam and its operation. Recent monitoring and research has shed light on direct and indirect influences of dam operations and these two important fisheries, as well as the aquatic foodbase of the CRe. Integrated studies of specific dam operations, such as high and steady flows, and their influence on multiple resources linked to both fisheries will help identify possible future options for fisheries co-management.

C.3. Key Monitoring and Research Questions Addressed in this project

This interdisciplinary project will use QW data collected by Project 2 (Topping and others), and foster collaboration between physical and aquatic Projects 3, 5 and 9, through the coordinated involvement of scientists that are already conducting research and monitoring in support of the GCDAMP and planning of a 20-year long experimental management plan being completed as part of the LTEMP EIS (see Grams and others; Korman, Yard and Kennedy, FY2013-14 BWP). These combined projects directly address the following Strategic Science Questions (SSQs), and Core Monitoring Information Needs (CMINs) previously identified by the GCDAMP, but through coordination provided by this project and the valuable products derived from Projects 3, 5 and 9, we will ensure a more direct linkage between existing channel sandbar mapping data and NO fish studies in an attempt to address the following questions and information needs relative to the three hypotheses identified above.

Primary SSQs addressed:

- **SSQ 1-3**. Do rainbow trout immigrate from Glen to Marble and eastern Grand Canyons, and, if so, during what life stages? To what extent do Glen Canyon immigrants support the population in Marble and eastern Grand Canyon?
- **SSQ 5-6**. Do the potential benefits of improved rearing habitat (warmer, more stable, more backwater and vegetated channel margins, more food) outweigh negative impacts due to increases in nonnative fish abundance?

Answering any of the above questions requires integrated analyses of fisheries and foodbase information with data from Project 3 (see Grams and others, FY2013-14 BWP), a project that has also identified information needs focused on sediment conditions monitored in the main channel of the Colorado River, including:

- **CMIN 8.6.1.** Track, as appropriate, changes in coarse sediment (> 2 mm) abundance and distribution.
- **CMIN 8.1.1.** Determine and track the biennial sandbar area and fine-sediment volume and grain-size changes within eddies below 5,000 cfs stage, by reach.

Although not specifically identified as an information need by the GCDAMP, Project 3 also provides critical information about bathymetry and "sand area and fine-sediment volume and grain-size changes" throughout long segments of the main channel below 5,000 ft^3/s stage outside of eddies in upper and lower Marble Canyon, as well as eastern Grand Canyon; areas containing intensive rainbow trout and native fish monitoring segments. The GCDAMP's DFC "Colorado River ecosystem" encompasses what was originally identified as the main sediment resource objective: "**Goal 8**: Maintain or attain levels of sediment storage within the main channel and along channel margins to achieve Adaptive Management ecosystem goals."

Generally, it is assumed that the sediment goal focuses on rebuilding and maintenance of higher-elevation sandbars along channel margins which can only be achieved by periodic high dam releases that re-suspend available sand from deeper parts of the main channel and lower eddies and redeposit it as sandbars. However, to date, there has not previously been any identification by managers about whether sand deposits covering the river bed have any role in the management of other non-sediment resources also described in the CRe desired future condition, such as nonnative trout, native fish or the foodbase. Despite guidance from managers about the role of fine sediment in the Colorado River channel outside of eddies, there has been prior recognition of the linkages between fine and coarse sediments in the channel and other CRe aquatic resources, as mentioned within the FY2013/14 biennial work plan (formerly Project A, now Project 3, Grams and others):

"Because sediment monitoring addresses the physical framework of the ecosystem, which underlies many biological resource objectives, Project A also indirectly supports achievement of:

- **Goal 1**: Protect or improve the aquatic food base so that it will support viable populations of desired species at higher trophic levels. The proposed monitoring supports this goal by providing information on the size and distribution of channel substrate.
- **Goal 2**: Maintain or attain a viable population of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats. The proposed sandbar and sediment storage monitoring supports this goal by providing information on sandbars which create backwaters, a habitat used by native fish."

Another overarching question identified by Grams and others (FY2013/14 BWP) during the last two years is: "What is the long-term net effect of dam operations, including high flows, on changes in low-elevation sand storage and bed sediment texture (the sand below the 8,000 ft^3/s stage)?" The answer to this question, perhaps as much as any other, is the one that we intend to integrate into 2017 NO analyses tied to NO fish catch and diet data provided by Project 5 researchers.

The strategy for ongoing channel mapping was initiated prior to the start of NO monitoring efforts in the FY2013/14 biennial work plan and before recent fish sampling suggesting trout reproduction in Marble Canyon. Therefore, there has been only limited opportunity for planning of integration between fish and sediment monitoring efforts before now. In light of new emerging information from juvenile trout catch data below Glen Canyon, coordinating additional bed imagery and topographic data collection is now critically needed in 2015–16 within NO study sites in Glen, Marble and eastern Grand Canyons. This effort will support multi-year integrated evaluation (2012–16) of fisheries and channel-bed sediment data (Table 1). Following, are summary descriptions of the tasks and methods associated with the seven project tasks within two elements proposed for 2015–17.

D. Proposed Work

D.1. Project Elements

As listed above, there are seven objectives of this integrated tailwater fisheries project to be achieved in three elements. One particularly critical objective likely has the most immediate management implications for co-management of native and nonnative fisheries below the dam. This is the assessment of the low-angle channel-margin areas inundated by most MLFF dam releases typically ranging from 5,000 up to ~25,000 ft^3/s. These are operations that have occurred since rainbow trout studies started in 2003, and have a direct influence on the nearshore areas that become available to trout fry after they emerge from redds (Korman and others, 2011). We believe that observations in summer 2011 by NO researchers of juvenile trout extensively using shallow inundated channel margins within Glen Canyon under high and steady dam operations, and the resulting survival of record numbers of rainbow trout fry that year (Korman and Yard, preliminary 2011 juvenile trout population estimate ranging from 0.8 to 1.2 million fish, 2012), warrant evaluation of the range of dam releases that create rearing areas for trout. As such, we anticipate the use for this type of information in planning future experimental flows that may be proposed to manage rainbow trout abundance below the dam. This information may be of particular interest to managers involved in the ongoing LTEMP EIS, and planning of a 20-year experimental management plan for Glen Canyon Dam operations.

Project Element 10.1. Refine Humminbird® Sidescan Sonar and Other Channel Mapping Methods to Support Fish and Foodbase Research

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Cooperator: Josh Korman, Fishery Biologist, Ecometric Research

Here, we intend to complete and document the methodology for determining changes in sand and gravel of channel-bed areas where trout are monitored by NO researcher in Glen, Marble and eastern Grand Canyons. This work is anticipated to be completed in FY2015, with methods being used through 2016 for ongoing post-processing of sidescan sonar channel-bed imagery. Results will support data collection and analyses needed to address three hypotheses associated with Project element 10.3.

Objectives:

- Define protocols for the best use of sidescan sonar to quantify spatial area of sand and gravel bed sediments of the Colorado River channel, as such the proposal includes provision for a graduate student, whose tasks will include:
- Developing completely or partially supervised bed sediment classification algorithms using existing sidescan data, collected in recent years, at high resolution with continuous coverage, based on calibrated echo strengths and texture (spatial pattern) of echoes,
- Validating these methods using concurrent video observations and sediment classifications based on multibeam backscatter (where available),
- Developing the computational advances necessary for correcting a boat-mounted sidescan sonar transducer for attitude instabilities (heave, roll, pitch and yaw), and evaluating the effects on sidescan sonar image quality, using data collected in Upper Marble Canyon in 2013 and eastern Grand Canyon in 2014,
- Evaluate the sensitivities in corrected geo-referenced sidescan amplitudes to uncertainties in attenuation due to sediment or gradients in sediment concentration, transducer location and boat heading,
- Developing the computational means by which sidescan can be corrected for bed slope effects when bed bathymetry is available, in which case it would be possible to correct for grazing angle effects on the sidescan echoes. The grazing angle is the angle made between the incoming acoustic beam and the local normal to the surface and affects the extent to which acoustic wave energy is reflected specularly and scattered diffusely. As such it represents a significant source of uncertainty in the image of the bed taken from multiple viewpoints (transducer locations and look angles). If the slopes are known along and across the beam, from existing bathymetries, a beam footprint can be accurately calculated and the backscatter value from each sidescan pixel modified by integrating over the area,
- Systematically characterize bed sediments in data collected in 2000 using a Klein towed-sidescan system, from RM0 to RM225 (preliminary data, Anima and others, 2007, US Geological Survey, Marine Geology Team, Pacific Science Center, Santa Cruz, CA).

Rationale/Justification

Topographic mapping and the collection of photographic imagery of the Colorado River's deeper channel bed below GCD have become an ongoing monitoring protocol to track changes in the spatially segregated distribution of sand area and sand volume with in the main channel and eddies of the Colorado River. This information supports sediment information needs of the GCDAMP, and is an integral part of monitoring in support of the 2012-20 HFE protocol. Dam operations are known to influence sand and gravel area coverage of the bed, and areas of coarser bed sediment are known to be used by benthic invertebrates and trout below the dam. As such, there is need to better document and evaluate changes over time in bed sediment type in response to tributary sediment inputs and MLFF dam operations, including high flow releases, particularly in key areas where fish and fish diet data are intensively monitored (NO, Project 9). Integrated analyses of bed mapping information with NO catch and diet data will then help identify how dam operations may influence and perhaps be used to manage not only sandbars, but also certain aquatic resources, such as trout and the foodbase.

The sediment make-up of the bed surface, which is exceptionally diverse in character, with the full spectrum of fine sand to boulders arranged in complicated spatial patterns, is constantly evolving and almost impossible to predict to any meaningful degree. That is, beyond generalized (and broad scale) observations of sand accumulating in eddies adjacent to sand-winnowed main channels, our prediction skill for a particular substrate or substrate mixture to be present in a particular location is poor. Bed sediment type is a boundary condition for which no predictive model exists. We therefore rely on observations of the bed which consists of: 1) the technology to image the riverbed surface with sufficient resolution that different substrates are distinguishable; 2) the accuracy and precision in positional measurements which make it possible to detect changes in individual locations through time; and 3) methods with which to accurately and efficiently (ideally unsupervised or partially supervised) estimate substrate type. Conventional sampling of submerged sediment deposits (e.g. grabs, cores, and dredges) is costly and labor-intensive. Video and photographic sampling is more cost-effective and does not require time-consuming laboratory analyses, which allows sampling at greater frequency and coverage (Rubin and others, 2007; Buscombe and others, 2014a). However, the use of high-frequency acoustic backscatter from swath-mapping systems to characterize sediment and classify by grain size (Anderson and others, 2008; Brown and Blondel, 2009; Brown and others, 2011) has the potential to provide near complete coverage, which photographic sampling could not practically achieve, at least within the same time and with the same positional accuracy. Completely capturing the variability bed sediment grain size with conventional physical or photographic sampling would be prohibitively costly and time-consuming.

Methods

We have recently developed a technique (Buscombe and others 2014b; 2014c) which automatically classifies sediments into 3 broad categories: 1) sand; 2) gravel (and sand-gravel mixtures); and 3) rocks (boulders and bedrock), based on the statistics of backscatter over these different sediments. Using this technique we're producing maps of substrates at unprecedented coverage and detail (figure 7). The method uses the spectral properties of the fluctuating component of backscatter over small spatial scales in combination with a machine-learning classification approach (decision tree). The method has been designed to be general in application with a solid physical basis. So far, 30 miles of river bed (lower Marble Canyon, LMC) have been classified at a resolution of 0.25 m^2, through a completely automated and unsupervised classification algorithm, using data collected in May 2012. The results have been validated using thousands of underwater video observations. The approach to sediment classification was able to classify patches of homogeneous sands, gravels (and sand-gravel mixtures), and cobbles/boulders with 95, 88, and 91% accuracy, respectively. The technique is currently being applied to other reaches mapped by Project 3 (LMC in 2009, eastern Grand Canyon (EGC) in 2011, and upper Marble Canyon, (UMC) in 2013). This work, which will be completed in 2014, will provide a full channel substrate map from RM0 to RM87, and a repeat substrate map for RM30 to RM61. Ongoing and future method development work (within Project Element 3.2) includes extending this technique so it is able to differentiate between sands and gravels of different sizes, as well as experimenting with the use of multibeam (MBES) backscatter to map submerged vegetation in Glen Canyon in 2015. With an operational method already developed for acoustic substrate classification, and several years of experience with collecting MBES data from the Colorado River in GCNP, we anticipate a rapid turn-around in data-processing which, for the first time, makes repeat mapping of substrates a realistic operational goal. To maximize efficiency, and minimize data collection costs, this data will be collected as part of Project Elements 3.2 and 3.4: namely, "Bathymetric and Topographic Mapping", which proposes to map the reach RM-15 to RM0 in 2015 (including Natal Origins (NO) reach 1), RM87 to RM165 in 2016, and RM0 to RM30 in 2017 (including NO reach 2, RM16 to RM 20); and "Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon", which is proposed to annually map in NO reach 4a upstream of the confluence of the Little Colorado and Colorado Rivers (RM60 to RM61).

Sidescan Sonar

The dynamics of the system are such that at a given location, sand coverage, and the spatial distribution of sand coverage, can vary significantly in time. Given the spatial heterogeneity of the Colorado riverbed, substrate estimates based on only a handful of observations at discrete locations are difficult to reliably extrapolate to reach-scale areal coverage of various substrate types. Physical sampling is also costly, laborious, and intrusive to organisms that call the riverbed home or use the bed to spawn. However, the use of acoustics for substrate mapping is non-intrusive and offers unparalleled spatial coverage and resolution.

The need to develop methodologies to map subaqueous riverbed sediment types is especially great when the water is too swift or deep to wade, too shallow for multibeam sonar, too turbid or deep to sense the bed from aerial imaging platforms, and/or when minimal logistics are required. The deployment of multibeam sonar requires a significant logistical overhead. Conventional underwater photographic imaging systems are limited by light attenuation, turbidity, and small spatial footprint of images when close enough to the bed to provide high resolution. A low-profile, pole- or transom-mounted sidescan sonar has the potential to meet this technical shortfall. Sidescan sonars image large swaths of the bed from a vessel, typically with decimeter to meter resolution depending on the range to the bed. The sonar sends out a high-frequency (several hundreds of kHz) acoustic pulse either side of the receiver and records the amplitude of the returning echo. With each pulse, a small strip of the bed is mapped, providing near continuous coverage as the boat moves slowly downstream. Coupled with a GPS or other type of vessel tracking, it can provide a continuous image of the bed, the texture of which can be used to infer the channel-bed sediment type. In addition to morphological form roughness, the strength of the returned echo is a function of the composition of the bed sediments. The basic premise is that, given the same roughness, a harder surface with greater acoustic impedance, such as rocks and cobbles, will return more energy than a softer bed such as sand. Inexpensive commercial sidescan systems are available which are designed to be mounted to small vessels and easy to use. They are also lightweight and have low demands for power, so could potentially be applied in any navigable river or stream, by as little as one person. Many modern sidescan transducers are very low profile and require minimal draft which means they are especially suitable for imaging in very shallow water. Kaeser and Litts (2010) reported that the sidescan sonar on the Humminbird® commercial fishfinder was sufficient quality for shallow water bed sediment mapping in shallow rocky streams. They were able to produce bed texture maps by merging and superimposing imagery onto a base map in a GIS, and manually identifying regions of similar bed texture on these maps (Kaeser and others, 2012). Since 2009, a Humminbird® sidescan sonar unit has been used opportunistically to image certain sections of the riverbed. We have tested this inexpensive sidescan sonar system in Marble and Glen Canyons in 2013 and 2014, establishing that the sonar is able to provide detailed images of the bed in water depths less than a meter (whereas MBES systems are limited to relatively deep water: >2m). The sonar provides an instant picture of the texture of the bed (figure 8) and can be used to map hundreds to thousands of square meters of riverbed in minutes (figure 9). Over the past year, we have improved upon the processing procedures of Kaeser and others (2012) by developing means by which to, in an automated sense:

1. Convert raw recorded sidescan amplitudes into units of acoustic power (dBW; decibel Watts). This potentially enables the derivation of acoustic/physical properties such as acoustic attenuation, bed roughness and hardness.
2. Correct the sidescan amplitudes for directivity attenuation, which depends on the geometry of the transducers and the beam shape of the acoustic wave, and acoustic attenuation by water and sediment, based on measured depth and estimates of the concentration and grain size of sediment in suspension.
3. Correct (partially) the sidescan amplitudes for angular effects imposed by the relative angle between the acoustic beam and the surface insonified by the beam (the acoustic footprint).
4. Apply geometric (slant-range) corrections to the data and estimate the orientation of scan lines, so it is possible to estimate the location of each sidescan pixel with greater accuracy, and which enables sidescan amplitudes to be processed as a geo-referenced point cloud.

Small, portable and lightweight sidescan sonars are easily deployable instruments for bed sediment reconnaissance surveys and the instantaneous qualitative assessment of large swaths of bed habitats. As such it is a technology which is, uniquely amongst its competitors, capable of providing rapid assessment of substrates over large areas of the bed, with minimal logistic overhead. In this proposal, we aim to build upon the recent advances listed above in a number of ways, all contributing to the aim of developing and utilizing robust and automated methods to relate sidescan image texture to different channel-bed sediment types, with an aim of producing maps of bed-sediments which are comparable in quality, resolution and reproducibility as those created using MBES backscatter. We aim to develop unsupervised (fully automated) or partially supervised (minimal user input) methods to classify bed sediments by grain-size using the echo strengths and/or the texture (spatial pattern) of echoes. If substrate classifications are carried out manually, this is not only time-consuming and labor-intensive (therefore expensive) but, in addition, the results are not necessarily reproducible (the same classifications obtained by different people, or by the same person at different times) unless a set of rigid protocols are in place. Such protocols would be difficult to achieve for sonar data across multiple instruments. The solution is to develop automated (unsupervised) or at least partially supervised (minimal user input) methods to classify large amounts of bed imagery in a consistent manner.

In summary, the aim of this work is to produce near-continuous (spatially explicit) maps of channel-bed sediment types, broadly categorized into sand, gravel, cobble and rock, at high spatial resolution (centimeters to meters). These techniques will be applied existing data sets (Table 1) previously collected in each of the NO reaches during 2012-14, as well as data which will be collected during 2015-2016, in support of the collaborative 5-year integrated analysis of fish and physical data described in Project Element 10.3.

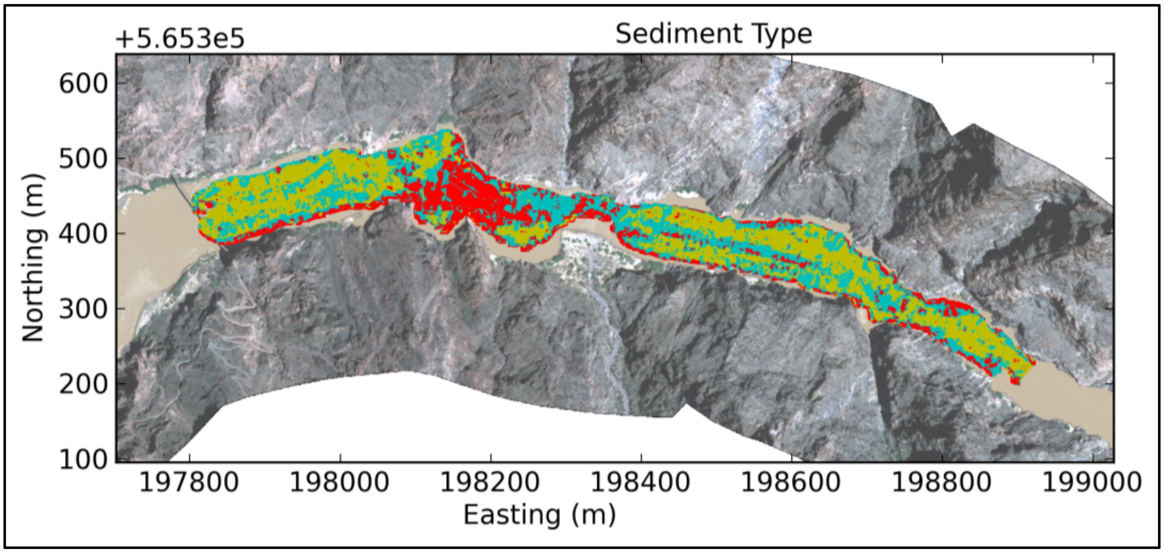

Figure 7. Map of riverbed sediments near Phantom Ranch in eastern Grand Canyon. Yellows are sandy bed, blues are gravels and mixed sand/gravels, and reds are rocky areas. This map has been created using a newly developed technique which relates the statistics of multibeam echoes to different types of riverbed sediments (preliminary data, Buscombe and others, U.S. Geological Survey, 2014).

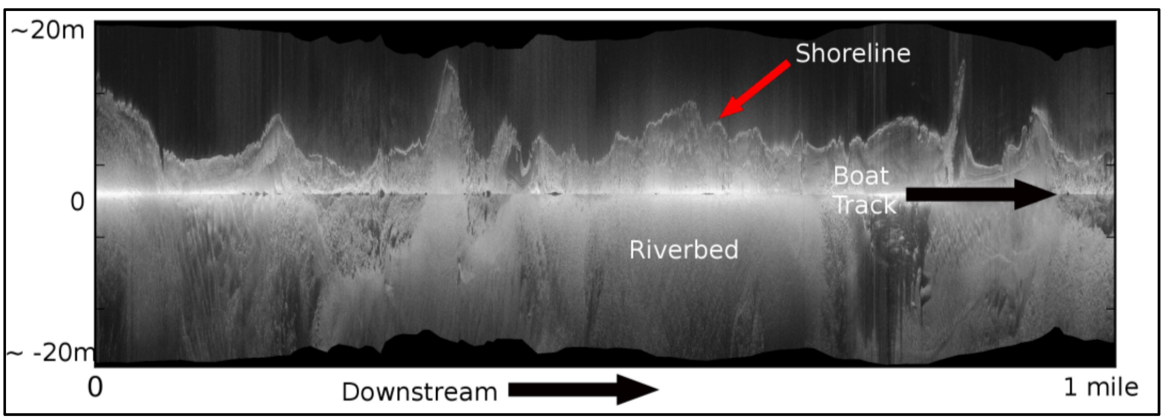

Figure 8. Example of "Humminbird®" sidescan imagery of the riverbed near -9 mile bar in Glen Canyon showing a patchy riverbed with fine to coarse gravels and clumps of submerged vegetation (shadow areas). Ongoing work is trying to relate each observed texture to a substrate type using underwater video for reference (preliminary data, Buscombe and Melis, US Geological Survey, 2013).

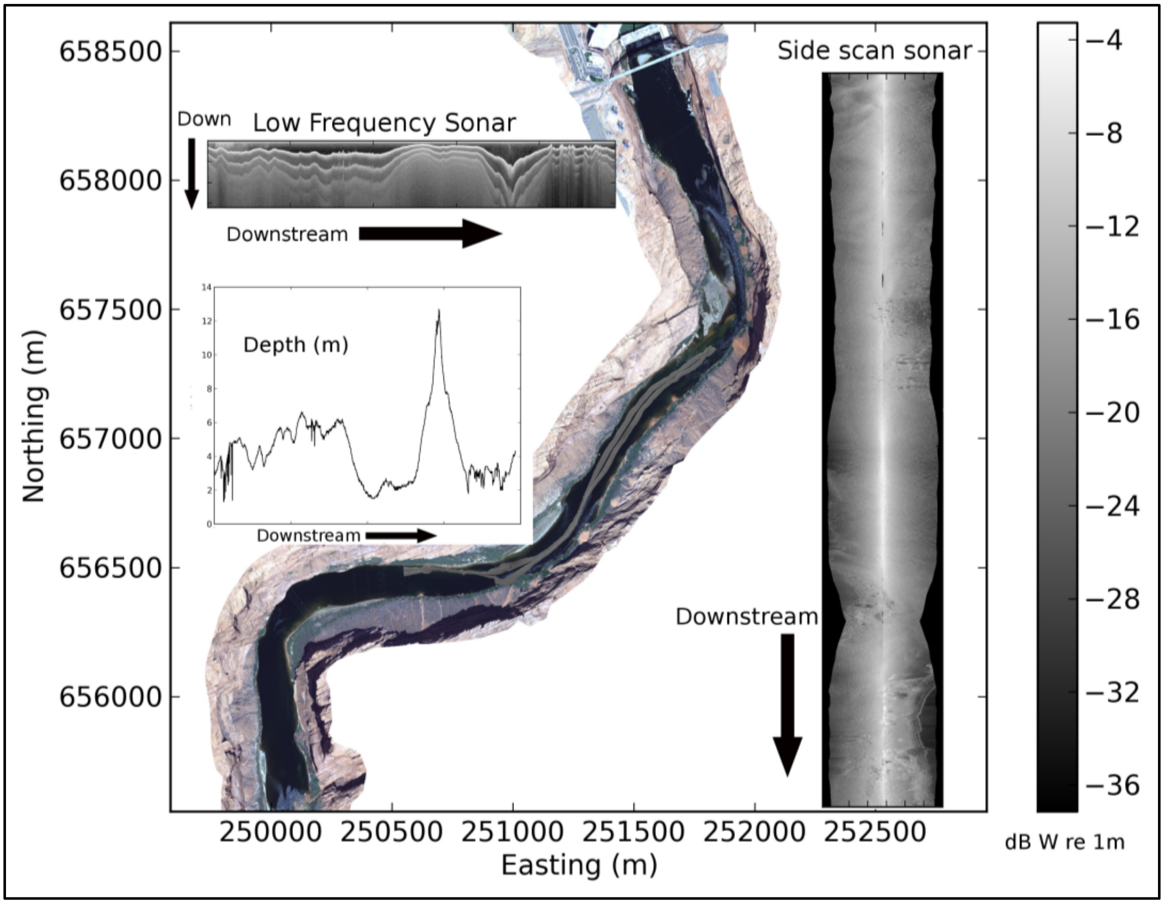

Figure 9. Example of "Humminbird®" sidescan imagery of the riverbed immediately downstream of Glen Canyon Dam showing a uniform coarse gravel bed. Units are decibel Watts, assuming a root-mean-square transducer output of 1000 Watts. It is standard convention to express this value 1m from the transducer. The inset panels show the trace from the low frequency sonar, and the depth sounding from under the boat (preliminary data, Buscombe and Melis, US Geological Survey, 2013).

Project Element 10.2 Collecting New Channel-Bed Humminbird® Sidescan Sonar and Digital Channel Margin Imagery, <u>and</u> Analyzing Channel-Margin Geometry, and Shoreline Responses to Flow Variation using Channel Map Data to Support Natal Origins of Rainbow Trout and Juvenile Humpback Chub Research

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Paul Grams, Research Hydrologist, USGS, GCMRC
Josh Korman, Fishery Biologist, Ecometric Research

Objectives:

- Collect new Humminbird® sidescan sonar imagery of the channel-bed and evaluate similar existing data to determine spatially segregated proportions of bed-sediment type within NO reaches 1 through 4 (see Table 1),
- Semi-annually in 2015-16, collect new Brinno® time-lapse digital imagery of shorelines during April and September intensive fish sampling trips in NO reaches 1 through 4.
- Evaluate changes in distributions of sand deposits along NO sampled shorelines between 2012 and 2017, using 2013 aerial imagery, existing Brinno® imagery collected in 2014, and new imagery collected through 2016,
- Spatially analyze shoreline geometry (proportion of slope angles less than 11 degrees used by juvenile trout) and gravel grain size distributions of low-angle channel margins throughout ***Glen Canyon***; then evaluate hypsometric characteristics of shorelines relative to changes in dam releases from 5,000 to ~25,000 ft^3/s using new Glen Canyon flow model (contingent upon funding for Wright and others, Project 5), in NO reach 1,
- Spatially analyze geometry (proportion of slope angles less than 11 degrees used by juvenile trout) of low-angle channel margins throughout NO reaches 2 – 4b of ***Marble and eastern Grand Canyon***s; then evaluate hypsometric characteristics of shorelines relative to changes in dam releases from 5,000 to ~25,000 ft^3/s using existing flow model (preliminary model, B. Logan, US Geological Survey, 2012) in NO reach 4b in eastern Grand Canyon,
- Summarize median seasonal and annual statistics for water temperature and total suspended-sediment, and turbidity measurements made in the Colorado River from available QW data collected in 2011-16, at monitoring sites between the dam and RM87.

Hypotheses/Questions:

1. <u>Hypothesis</u> - Operations of Glen Canyon Dam result in progressive winnowing of the channel-bed to the extent that coarsened bed sediments of the main channel, combined with ongoing tributary inputs of gravel, and QW conditions, increasingly support life history requirements of nonnative rainbow trout within and below Glen Canyon. <u>Questions:</u> **1)** Are grain-size distributions of low-angle gravel bars throughout ***Glen Canyon*** similar between the dam and Lees Ferry? **2)** Do proportions of sand and gravel areas of the deeper channel bed channel in NO reaches 1 through 4 vary annually (within detection limits) between 2012 and 2016, and if so, then by how much? **3)** Do proportions of sandbar mantled shorelines in NO reaches 1 through 4 vary annually

between 2012 and 2016, and if so by how much? **4)** Is there a multi-year trend in the relative proportions of channel-bed sand and gravel area within NO reaches 1 through 4, and if so, then do variations correspond with release of high flows from GCD, and annual fine-sediment supplied to the Colorado River from the Paria and Little Colorado Rivers?

2. Hypothesis - Geomorphic differences of the Colorado River's channel geometry within NO study sites 1 & 4b, combined with behavior of flow and stage, result in varied channel margins, and these differences influence fish access to near shore areas in ways that limit the influence of how hourly changes in flow affect trout below GCD relative to their distribution, abundance, growth and survival of age-0 rainbow trout. Questions: 1) Is the abundance and distribution of low-angle (less than 11 degree channel-margin slopes), consistent throughout NO reaches 1 - 4b? **2)** Are shorelines associated with low-angle (less than 11 degree slope) channel margins most sensitive to changes in dam operations on the basis of modelled shorelines over a range of 5,000 to 25,000 ft^3/s within NO reach 1 (lower Glen Canyon) or 4b (eastern Grand Canyon below the LCR)?

Rationale/Justification

Gravel spawning areas for rainbow trout in Glen and Marble Canyons have been previously described (Korman and others 2005; Kondolf and others, 1989, Maddux and others, 1987). Trout spawning continues to be monitored in Glen Canyon annually as continuation of the rainbow trout early life-stage survival (RTELSS) studies initiated in 2003 to study effects of experimental fluctuations on trout egg survival (*see element 9.2*). However, much less is known about whether spawning gravel area grain sizes used by trout in Glen Canyon have changed at sites such as Four Mile Bar over time, or whether new trout spawning areas have evolved downstream in Marble Canyon since initial studies were done by Kondolf and others (1989) in the 1980s.

Previously collected bathymetric and digital imagery of Marble Canyon have been obtained through a variety of methods associated with earlier mapping and monitoring projects and are available in FY 2015 for use in development of quantitative methods for estimating areas below Glen Canyon with suitable rainbow trout spawning substrates. This research is needed now, as preliminary 2013-14 data from the NO project suggest local production of rainbow trout below Glen Canyon (fig. 3) has occurred since the project started in fall 2011 (Korman and others, Ecometric Research and USGS, preliminary data). Sand budgeting and channel bathymetry data collected from 2009 to 2012 from lower Marble Canyon (Grams and others, USGS, 2014, preliminary data) also suggest that dam operations since 2009, such as the 2011 extended high releases, have created a sand deficit in this segment such that channel-bed conditions below river mile 30 may be highly winnowed of finer sediment. The winnowed bed of the channel, combined with changing water quality, may have made Marble Canyon more suitable recently for rainbow trout spawning and rearing of juveniles; in effect, extending the favorable conditions for trout found in Glen Canyon to areas downstream of Lees Ferry.

Topping and others (2003) report that dam operations under MLFF during the 1990s resulted in flows exceeding those required to accumulate sand on the river bed between Lees Ferry and Phantom Ranch – by about a factor of two compared to the pre-regulated era (figure 6-right). This fact also further supports the idea that MLFF dam operations since 1996 have likely winnowed bed conditions in parts of lower Marble Canyon where rainbow trout from natal origin areas upstream might find suitable channel-bed spawning areas after moving downstream from Glen Canyon. Because typical MLFF dam operations were shown to limit accumulation of multi-year tributary sand inputs on the bed of Marble Canyon after 1996, a protocol was implemented in 2012 to experimentally determine if more frequent HFEs could rebuild and maintain sandbars following Paria River tributary floods. More frequent HFEs that deposit sand deposits from the deeper channel to channel margins within eddies may, however, also create conditions of bed winnowing in deeper parts of the channel in lower Marble Canyon; scoured areas that perhaps expose areas of the bed with coarser grain sizes (see fig. 15 of Project Element 3.4, above); areas perhaps suitable for spawning by rainbow trout.

Methods

Below Glen Canyon, submerged areas of Marble and eastern Grand Canyon have been previously mapped at high resolution (Grams, Buscombe and others, preliminary data, USGS, 2014) multi-beam sonar, but discharge and inundation characteristics of nearshore habitats used by juvenile trout have not been previously evaluated downstream of Lees Ferry. The location of the USGS gage at 61-Mile (gage 09383100), also provides an opportunity to document channel margin habitat inundation upstream of the Little Colorado River confluence, while existing channel bathymetry data downstream of the Little Colorado River to about river mile 64, and an existing 2-dimensional flow model (B. Logan, preliminary model, USGS, 2012) now make evaluation of nearshore habitat in these reaches also possible in 2015-17.

In 2015, using existing 2004 channel bathymetry data, 2009 digital surface model data, and available 2-dimensional cross-sections to estimate flows, we will estimate hypsometric curves associated with shorelines that vary with dam releases along channel margins where rainbow trout and native fish sampling by NO researchers is ongoing between 2012-16. Products will include maps showing channel margins inundated by flows of 5,000, 8,000, 15,000, and 25,000 ft^3/s, and this channel geometry information will also support data needs of food base researchers (see Project Elements 5.2.2 and 5.2.4). As shown in Table 1, Project 3 researchers will collect new channel map data in Glen Canyon during 2015 (see Project Element 3.2, above), to provide a full-channel topographic and channel-bed sediment map for Glen Canyon, in part, to support more integrated evaluations of channel characteristics and fish data collected as part of the NO project (Project 9). These new data will be used in 2016 to develop a Glen Canyon flow model that can then be used to improve modelled shorelines in NO reach 1, and extend similar hypsometric channel margin analyses upstream to other low-angle channel margin areas used by juvenile trout. We will also use the new 2015 channel data to conduct Arc® map based evaluations of the abundance and distribution of low-angle channel margin areas throughout Glen Canyon, with particular emphasis within NO reach 1 and the Four Mile Bar, as this segment contains a point bar that is frequently used by sport anglers, and on that is also annually monitored for redds as part of rainbow trout early life-stage survival (RTELSS) effort (see Project Element 9.2).

As described above, in an attempt to better use channel-bed imagery data to support fish and foodbase research, Buscombe and others, will develop completely or partially supervised channel-bed sediment classification algorithms using existing sidescan data and validate these methods using concurrent video observations and multibeam backscatter. They will also pursue computational advances necessary for correcting a boat-mounted sidescan transducer for attitude instabilities (heave, roll, pitch and yaw) and evaluate the effects on sidescan image quality, using data collected from Marble Canyon in 2013 and eastern Grand Canyon in 2014.

Using the computational means developed in 2015 from Project Element 10.1 (above), by which sidescan data can be corrected for bed slope effects, when bed bathymetry is available, we will also systematically characterize channel bed sediments in sidescan sonar imagery collected in September 2000 (Anima and others 2007). Data from this era prior to intensive rainbow trout sampling and research will provide a historical context for bed-change mapping results using data from 2011-16, particularly in Glen Canyon where RTELSS monitoring has been ongoing for more than a decade. Within detection limits of data and methods used for image analysis and mapping, we will identify spatial and temporal trends in sand and gravel area of the channel bed from existing channel-bed topographic or imagery data collected within four NO study reaches (and to the extent possible, adjacent segments upstream) between 2012 and 2016. This is the main interpretive physical resource element intended to link areas of the channel associated with 1) drifting and emergent insects (*Projects 5.1 and 5.2*), and 2) rainbow trout spawning and early life history (*Project 9*) to changing physical conditions of the Colorado River channel (*Project 3*), in the context of other quality-of-water environmental attributes (turbidity and water temperature) within Glen and Marble Canyons (*Project 2*) already being evaluated within the 2015–17 budget and workplan.

Glen Canyon Low-Angle Channel Margins & Grain Size

In addition, we will document surficial grain size distributions of gravel bars associated with these fish monitoring shorelines using digital images collected at approximately the 8,000 ft^3/s shoreline elevation at each sample site. Size distributions will be determined using the algorithm of Buscombe (2013; example shown in figure 10 here) and these data will be evaluated to identify longitudinal trends in grain size along channel margins used by trout between GCD and Lees Ferry. Riebe and others (2014) report that trout length may be associated with gravel particle size in channel settings where fish build redds. Following after this finding, we will measure surficial grain size in channel margin areas of Glen Canyon where redds are typically observed and compare them with trout catch data from NO fall marking trips in Glen Canyon to evaluate whether either trout abundance and/or length are related to gravel size distributions.

We will also determine shoreline and dam release relationships along low-angle channel margins within NO study reach 1 with emphasis on Four Mile Bar; an area used by juvenile trout in Glen Canyon (Korman and others, 2011). This work is intended to more accurately identify areas of Four Mile Bar that are most sensitive to changes in dam releases; information that can be used to inform hydrograph design(s) of experimental trout management dam releases that might be implemented under LTEMP as strategy to regulate early life history stages (age-0) of rainbow trout, and later using existing 2000-era cross sections (local 2-D rating curves) and 2015 channel bathymetry data for entire Glen Canyon segment in 2016. Using underwater video imaging systems, we will also determine aquatic vegetation characteristics of selected areas of the river bed at 500-m spacing between Eight Mile Bar and Lees Ferry above and below 8,000 cfs to support ongoing development of a potential primary production model (Yard and others).

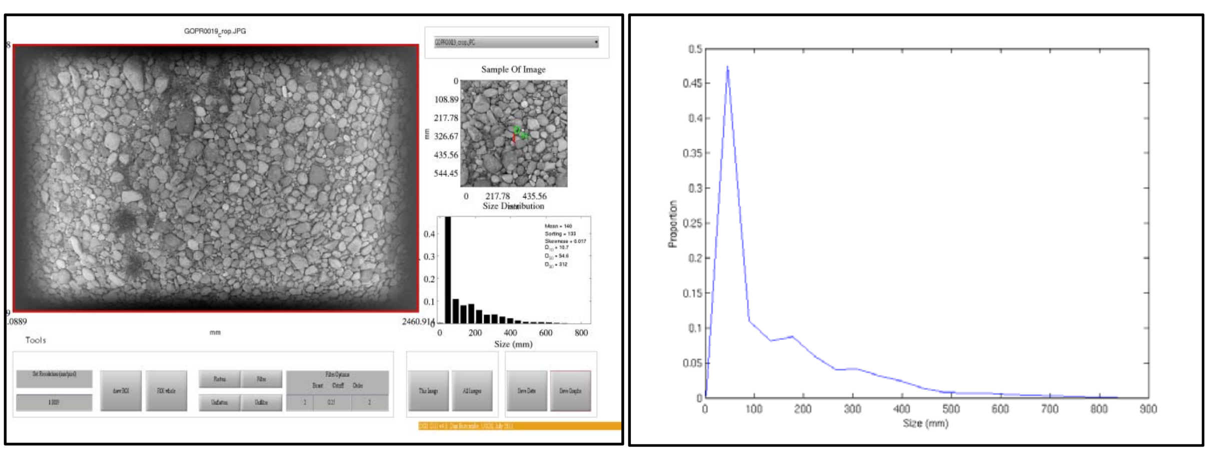

Figure 10. Example of coarse-grained size distribution derived from digital still image taken from the surface of a point bar located along the river right shoreline about 9 miles upstream of Lees Ferry in Glen Canyon (preliminary data, Buscombe and Melis, US Geological Survey, 2013), using the algorithm of Buscombe (2013).

Use of Marble and Eastern Grand Canyon Map Data to Assess Channel Margins

We will produce information similar to what derives from task 3 above, but for existing mapped segments of Marble and eastern Grand Canyon - physical channel geometry data needed for addressing NO issues regarding spatial heterogeneity effects on capture probabilities within and among NO study reaches 2 - 4b (see project element 9.2). This will be undertaken using ARC® Map slope analysis tools to evaluate May 2012-13-14 topographic channel data collected by Grams and others for sandbar monitoring. Additional multibeam data may also be collected as part of Project 3 in 2015-17 in NO reaches 4a and 4b as part of bedload sediment transport studies proposed by Grams and others. An existing flow model (preliminary model, B. Logan, US Geological Survey, 2012) will also be used to identify shoreline and flow relationships within NO reach 4b below the confluence of the LCR and the Colorado River.

This information will then be used to compare the sensitivity of channel margins to flow changes below the LCR, where trout and juvenile chub are monitored, to similar changes in dam operations upstream within NO reach 1 (Four Mile Bar) and possibly at other upstream low-angle channel margin settings. Differences in shorelines in response to varied dam releases between lower Glen and eastern Grand Canyons will inform fish scientists and dam managers about the potential for designing and testing experimental trout management flows in these river segments relative to use of low-angle channel margins by juvenile trout.

Estimating Relative Proportion of Sand and Gravel in Deeper Channel

Using the methods developed and documented in 2015 by task #1, we will determined the time-varied spatial distributions of gravel and sand area exposed along channel margins and the deeper channel bed of the Colorado River that are known to be used by rainbow trout in Glen Canyon. In Marble and eastern Grand Canyon river segments, we will conduct similar assessments in deeper areas of the channel bed to identify areas that may represent potential spawning gravel used by trout below the Paria and Little Colorado River confluences. The evaluation will be done using pre-existing and new Humminbird and multibeam data specifically within or upstream of NO reaches 1 - 4b in 2016; Buscombe, Melis, Gushue, and others.

Estimating Relative Changes in Proportion of Sand Mantled Shorelines in NO Study Sites

Evaluating possible influences on fish catch rates in NO study reaches 1 - 4b between 2012-16, associated with changing shoreline and near-shore sandbar deposits (low elevation eddy and lower channel sandbars) that may result from tributary sand inputs combined with high flow dam operations. To identify channel-margin changes in NO sample sites, we will examine shorelines imaged within NO study sites in 2009 and 2013 (digital overflights flown at 8,000 ft^3/s), and compare sediment and vegetation conditions of those shorelines, with Brinno® time-lapse digital camera imagery collected at the study sites on NO fish sampling trips during spring 2014, and September and April 2015-16. The imagery will also be evaluated in the context of the geomorphic base map being developed by Project 3 (Grams and others) in Glen, Marble and eastern Grand Canyons. Changes in sandbar distribution along channel margins between 2013 and 2016 will be evaluated relative to fish catch data from the NO project to determine whether or not sediment characteristics of shorelines influence use of channel margins by rainbow trout and native fish. Using Brinno® time-lapse digital cameras, we will image and evaluate channel margins in September and April during times when NO rainbow trout catch data are collected and when shorelines are imaged at relatively lower flows associated with “shoulder season” or reduced monthly dam release volumes that tend to expose larger channel margin areas.

In this task, we believe we have two unique opportunities to assess possible influences of sandbar deposition along shorelines on fish catch. First, within NO site 1, up and downstream of Waterholes Canyon. Summer 2013 flooding from this ephemeral tributary appears to have altered the lower portion of this most upstream NO study reach; perhaps to an extent that has altered trout distribution in Glen Canyon. Trends in trout catch data from 2011 through 2016 collected above and below Waterholes Canyon will be evaluated relative to the timing of Waterholes Canyon flooding and high flows from the dam to determine whether or not the 2013 sediment inputs altered fish abundance and distribution in reach 1. Downstream, in Marble and eastern Grand Canyons, we will also evaluate changes in sandbar abundance along channel margins in NO study sites 1 through 4, to determine possible influences of Paria River sand inputs and HFEs that may occur in 2014-16, and compare them with fish catch data; Melis, Buscombe, Grams and others, in collaboration with Yard and Korman.

Project Element 10.3. Integrated Time Series Analysis of Physical Channel Mapping, Quality-of Water, and Natal Origins of Rainbow Trout and Juvenile Humpback Chub Catch and Diet Data

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Mike Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, Fishery Biologist, Ecometric Research
Dan Buscombe, Research Geologist, USGS, GCMRC
Paul Grams, Research Hydrologist, USGS, GCMRC
Tom Gushue, GIS Coordinator, USGS, GCMRC
GS-9 Geographer, USGS, GCMRC
Other aquatic biologists, and invited synthesis workshop expert participants, USGS and GCDAMP stakeholders

Objectives

1. Identify spatial and temporal correlations between adult and age-0 rainbow trout abundance, growth rates, and channel-bed and channel-margin sediment type (sand and coarser grain sizes) within NO reaches 1 through 4b,
2. Compare multi-year trends in NO fish catch data, with seasonal to annual variation in median water temperature and total suspended sediment data (turbidity), the frequency, magnitude and seasonal timing of high-flow dam releases, relative to frequency and magnitude of Paria and Little Colorado River fine-sediment inputs to the Colorado River between 2011 through 2016,
3. Identify spatial and temporal correlations between age-0 rainbow trout abundance and growth rates and the distribution of low-angle (11 degrees slope or less) channel margins throughout Glen Canyon, and within NO study reaches 1 through 4b,
4. In collaboration with Project 3, 5 and 9 researchers, evaluate trends in foodbase and rainbow trout diet relative to 2011-16 changes in fish catch and channel-bed sediment type in NO reaches 1 through 4.

Hypotheses/Questions

1. Hypothesis - Operations of Glen Canyon Dam result in progressive winnowing of the channel-bed to the extent that coarsened bed sediments of the main channel, combined with ongoing tributary inputs of gravel, and QW conditions, increasingly support life history requirements of nonnative rainbow trout within and below Glen Canyon. Question: Do trends in mapped areas of sand and gravel along channel margins and within the deeper channel bed in NO reaches 1 through 4b, change between 2011 and 2017, and if so, then is there any correlation between bed sediment type, adult or age-0 rainbow trout abundance and growth-rate, or juvenile humpback chub survival data?
2. Hypothesis - Increasing frequency of higher and warmer releases from Glen Canyon Dam increases rainbow trout production in the GCD tailwater regardless of seasonal timing, but this response is also spatially controlled by the abundance and distribution of fish in Glen, Marble and eastern Grand Canyons, as well as the timing, frequency and magnitude of Paria River floods. Question: How has the discontinuity distance below GCD changed through time relative to the CRe's thermal and turbidity regimes relative to NO project catch data for adult and age-0 rainbow trout abundance and distribution?

Rationale/Justification

Ongoing monitoring of aquatic resources of the CRe, including fish, foodbase, quality-of-water and sediment, have now been underway to support information and research needs of the GCDAMP since the late 1990s through GCMRC's science program. Over time, new finding about how each of these individual resources is tied to operation of GCD has grown. Earlier, learning about how dam releases influence fine and coarse sediment in GCNP was advanced rapidly by monitoring of the spring 1996 Beach/Habitat Building Flow experiment, as well as sediment-transport and channel monitoring of sandbar thereafter (Schmidt and Grams, 2011b; Topping and others, 2000). Understanding about how dam operations influence rainbow trout and the foodbase in Glen Canyon were advanced initially following integration of single-resource monitoring during and after the March 2008 HFE (Korman and others, 2011; Cross and others, 2012). Knowledge about food web dynamics, dam operations and fish in the CRe was also advanced by research that focused on trophic linkages below the dam over the last decade

(Cross and others, 2013; Kennedy and others, 2013). On the basis of these recent advances intended to better inform managers about options for operating GCD to achieve downstream resource goals tied to Desired Future Conditions in GCNRA and GCNP, new research to synthesize physical and aquatic data over a multiple year period is now needed. The outcome of the project 9 synthesis is intended to provide greater understanding about how specific GCD operations influence the channel bed and margins of the CRe, and in turn how changes in those physical resources may influence fish and the foodbase over distances that might vary downstream of the dam through time. In undertaking this synthesis, we propose to address the question about where the GCD tailwater ends below the dam.

Methods

Synthesis Workshop 2017 - The project's seventh element is the main objective of the project, which is to achieve a synthesis of physical and aquatic monitoring data and research findings from the NO fisheries and physical channel mapping and QW projects. The aim here is to better understand whether and how specific dam operations may be influencing the downstream length of the GCD tailwater fisheries, particularly in terms of rainbow trout and humpback chub dynamics and interactions, as well as trout diet related to the CRe foodbase. This will be a collaboration between aquatic biologist and sediment scientists; one that is initiated through a 2-3 day integrated workshop with participants from Projects 3, 5 and 9, as well as other invited experts. The timing of this activity is proposed for some time during the first half 2017, and following the proposed Project 9 Protocol Evaluation Panel (PEP) 2016 review meeting to allow input from the PEP to also be considered by workshop participants. Workshop participants will present findings from individual research and monitoring projects to promote sharing of information among synthesis team members. The first step in synthesizing the available physical and biological data will be to overlay time series for rainbow trout catch data, with channel map information related to bed-sediment type within each of the NO study reaches using available data from 2012-16. The objective of the workshop is to refine approaches for further analyses and toward completion of an interpretive report on integrated research findings from the NO project's 5-year intensive fish monitoring of trout origins, movements, diet and juvenile humpback chub survival in the Colorado River below the Little Colorado River.

Strategies for further analyzing available time series data to identify spatial and temporal patterns in rainbow trout catch and diet, relative to measured variations in channel characteristics and QW of the CRe downstream of the dam in the GCD tailwater, will be reviewed and discussed among team members to develop approaches for further analyzing spatial and temporal patterns of fish catch trends within the GCD tailwater. Strategies for integration physical and aquatic data sets into fisheries and productivity models developed by Projects 2, 3, 5 and 9 will also be identified. In the 2017 workshop, the 2012-16 fish and other biological resources (such as riparian vegetation changes derived from Project 11), and physical resource information will also be evaluated and discussed in context of earlier ecosystem modeling exercises that were formerly undertaken by GCMRC and cooperators in the late 1990s and mid-2000s. In the spirit of these early conceptual modeling efforts, GCDAMP stakeholders will participate in the final day of the project's synthesis workshop.

While many other factors likely influence the distribution and abundance of rainbow trout below the dam, our synthesis of physical and available biological data will provide new perspectives about the possible role of dam operations as a factor influencing these aquatic resources throughout Glen and Marble Canyons (abiotic/biotic synthesis of dam operations within the upper 1/3 of the CRe), and will also inform managers about possible value or need for continuing similar integration of physical and biological strategies in future long term monitoring of the CRe.

D.2 Personnel and Collaborations

The majority of researchers is located at the US Geological Survey's Southwest Biological Science Center, GCMRC, but is largely dependent upon ongoing collaboration with cooperator J. Korman of Ecometric Research (Vancouver, BC).

D.3 Deliverables

Project element 10.1 - Manuscript on research and development of new methods for using Humminbird® sidescan sonar instruments for imaging channel-bed sediment type and sediment changes in channel margin settings to support aquatic resource monitoring, Buscombe and others proposed for 2016.

Project element 10.2 – New topographic and channel-bed sediment type maps (Grams, Buscombe and others collected in 2015 and proposed to be available for further analyses by 2016). Preliminary USGS report in 2015 on slope analyses of existing 2004 & 2009 full-channel topography of Glen Canyon related to proportion of low and high-angle channel margins (Melis and Gushue).

Project elements 10.3 and 10.4 – USGS final report (Melis and others proposed for 2016) on spatial channel-geometry (channel margin slopes) variations along the Colorado River within selected segments of Glen, Marble and eastern Grand Canyons, with focus on modelled flow in channel margin areas (NO reaches 1 & 4b, contingent upon flow model development being funded for Glen Canyon) relative to channel margins used by early life stage rainbow trout.

Project elements 10.5 and 10.6 – Time series analyses of spatially segregated distribution of sand and gravel areas of the Colorado River channel bed within NO study sites 1, 3, 3, 4a and 4b between 2011 and 2016. USGS report by Melis, and others (proposed for 2016-17).

Project element 10.7 – Interdisciplinary spatial analysis of 5-years of abiotic and biotic data, Melis and others (2017 manuscript) on multi-year rainbow trout catch and diet data relative to mapped changes in channel-bed sediment type (sand and coarser grained bed sediment) in Glen, Marble and eastern Grand Canyons study sites associated with NO project. Also, presentations at conferences and annual progress reports to GCDAMP stakeholders on Project 10 elements.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

None to date, owing to new project status, but the proposed interdisciplinary research builds upon numerous physical and biological data products from other ongoing projects preceding this integration (see Projects 2, 3, 5, 9).

E.2. Completed Publications

None to date, owing to new project status, but the proposed interdisciplinary research builds upon various publications from other ongoing projects preceding this effort (see Projects 2, 3, 5, 9).

E.3. Publications in progress

Buscombe and others, currently have three manuscripts submitted and in review on development of methods for imaging channel-bed substrates on the basis of 2013-14 Colorado River research conducted under Project 3 (Grams and others) that supports the Element 10.4.1:

Buscombe, D., Rubin, D.M., Lacy, J.R., Storlazzi, C., Hatcher, G., Chezar, H., Wyland, R., and Sherwood, C., 2014a (accepted for publication), Autonomous bed-sediment imaging-systems for revealing temporal variability of grain size: *Limnology and Oceanography: Methods*; Buscombe, D., Grams, P.E., Kaplinski, M.A., 2014b (in review), Characterizing riverbed sediments using high-frequency acoustics 1: Spectral properties of scattering: *Journal of Geophysical Research - Earth Surface*; and Buscombe, D., Grams, P.E., Kaplinski, M.A., 2014c (in review), Characterizing riverbed sediments using high-frequency acoustics 2: Scattering signatures of Colorado River bed sediments in Marble and Grand Canyons: *Journal of Geophysical Research - Earth Surface*.

E.4. Presentations at GCDAMP meetings

PowerPoint Presentation: GCDAMP Annual Reporting Meeting, Phoenix, AZ, January 29, 2014, "Low flows in Glen Canyon: preliminary geomorphic analysis of the potential effects on fish and food base", by T.S. Melis[a], T. Gushue[a], T.A. Kennedy[a], J.D. Muehlbauer[a], M.D. Yard[a], P.E. Grams[a], J.B. Sankey[a], K. Kohl[a], T. Andrews[a], J.E. Hazel Jr.[b] and J. Korman[c]

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Poster Sessions: "PRELIMINARY LOW-FLOWS STUDY IN THE LEES FERRY TAILWATER BELOW GLEN CANYON DAM" January TWG, and February AMWG meetings, Phoenix, AZ, by T.S. Melis[a], T. Gushue[a], T.A. Kennedy[a], J.D. Muehlbauer[a], M.D. Yard[a], P.E. Grams[a], J.B. Sankey[a], K. Kohl[a], T. Andrews[a], J.E. Hazel Jr.[b] and J. Korman[c]

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E.5. Presentations at professional meetings

None to date, owing to new project status, but the proposed interdisciplinary research builds upon various presentations from other ongoing projects preceding this effort (see Projects 2, 3, 5, 9).

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... and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
				FY15							
	10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$123,500**	**$5,000**	**$0**	**$0**	**$0**	**$0**	**$20,100**	**$148,600**
				FY16							
	10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$129,800**	**$5,000**	**$0**	**$0**	**$0**	**$0**	**$28,700**	**$163,500**
				FY17							
	10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$96,800**	**$7,000**	**$0**	**$0**	**$0**	**$0**	**$28,400**	**$132,200**

uscombe, Yard, Korman and Grams, derived from Projects 3 & 9 budgets. 2. USGS salary support is distributed as follows: **2015** -
grapher 2 PP, Student Pathway 18 PP; **2016** - Melis 11 PP, Gushue 4 PP, Geographer 2 PP, Student Pathway 18 PP; **2017** - Melis 11
PP. 3. USGS indirect cost rates applied to estimated direct costs shown in 2015-17, were calculated at 16, 22 and 28% respectively,
for non-GCMRC USGS or non-USGS cooperators in this project budget.

Project 11. Riparian Vegetation Monitoring and Analysis of Riparian Vegetation, Landform Change and Aquatic-Terrestrial linkages to Faunal Communities

Initial Estimate: FY15: $488,100; FY16: $551,700; FY17: $504,500

GCDAMP Funding: FY15: $488,100; FY16: $513,100; FY17: $479,300

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John Spence, Resource Manager, National Park Service, Glen Canyon National Recreation Area

B. Project Summary

Riparian vegetation affects physical processes and biological interactions along the channel downstream of Glen Canyon Dam. The presence and expansion of riparian vegetation promotes bank stability, diminishes the magnitude of scour and fill during floods, and has a role in wildlife habitat and recreational values. This project utilizes annual field measurements and digital imagery for integrated monitoring of changes in vegetation assessed within a hydro-geomorphic context. Research elements of this project utilize the monitoring data to explore the utility of plant response-guilds to probabilistically evaluate and assess wildlife habitat, and integrate the response guilds with a 22-year topographic survey record for retrospective analyses of topographic change of 20 sandbars. This project builds upon accomplishments associated with the FY13/14 Work Plan, provides information that support stakeholder needs as identified by guiding documents developed by the Adaptive Management Program, and furthers our understanding of the role of riparian vegetation in ecosystem processes in a regulated river ecosystem.

The objectives and elements of this monitoring and research project are:

1. Measurement and analysis of plant cover and species presence to assess change as related to the geomorphic setting, elevation above the channel, and flow regime (Project Element 11.1)
2. Mapping changes in woody vegetation at the landscape scale through image processing, classification, and analysis (Project Element 11.2)
3. Utilizing vegetation response-guilds for integrated research of sandbars and riparian vegetation (Project Element 11.3)
4. Use multiple sampling approaches and historic data sets to quantify the strength of aquatic-terrestrial linkages and the relative importance of vegetation change and aquatic production in driving the population dynamics of a subset of the terrestrial fauna (Project Element 11.4).
5. A review and assessment of nonnative plant control and native plant restoration efforts along regulated segments of the Colorado and Rio Grande Rivers (Project Element 11.5).

Each of these objectives and the associated project elements inform stakeholders about the status of vegetation and support analysis of vegetation's role in the ecological, physical, sociocultural responses to dam operations.

C. Background

The abundance, structure, and location of riparian plant species reflect differential responses to substrate properties, channel geomorphology (e.g., width, depth, bed and bank material, slope, floodplain functionality), and flow regime (Auble and Scott 1998; Mahoney and Rood 1998; Auble and others, 2005; Naiman and others, 2005). Species that respond similarly to these geomorphic and hydrologic processes can be categorized into response-guilds (Grime, 1979; Lavorel and Garnie, 2002; Merritt and others, 2010). Alteration of the flow regimes due to regulation by dams changes the disturbance regime and hydroperiod across channel margins and leads to changes in the plants that dominate the landscape: river regulation contributed to the dominance of tamarisk (*Tamarix* sp.) and Russian olive (*Elaeagnus angustifolia*) along the majority of the streams and rivers in the southwestern United States (Stromberg and others, 2007; Birken and Cooper, 2006; Merritt and Poff 2010). River regulation is thus a selective force on riparian communities and shifts the dominant species and associated response-guilds found along channel boundary.

The nine preliminary response-guilds identified from the 2012-2013 field collections (fig. 1, Table 1) are a unifying component of each element of the riparian vegetation project (Project 11) in FY15–17. Annual, ground-based vegetation plot data that are associated with hydrologic zones (see methods 11.1) of inundation frequency are used to develop a guild flora (species groups based on physiological and morphologic traits measured and recorded in the literature).

Changes in the frequency of guilds encountered at fixed and random sampling sites can be used as a tool to interpret vegetation response to flow regimens (for example, reduced annual water volumes may increase the frequency of occurrence of group B - Drought tolerant well dispersed, ruderal herbs/grasses observed in stage elevations above 25,000 ft^3/s). Monitoring vegetation within a hydro-geomorphic framework permits the identification of response guilds along a river channel and among geomorphic features.

Monitoring that includes landscape-scale change detection enables an assessment of the extent of observed ground-based changes across the landscape and answers questions such as: Is a trend of more plants adapted to xeric conditions along one river segment similar to that observed elsewhere? Is a trend of vegetation-type or amount specific to sandbars or channel margins or common to all or most features along a river channel? Annual ground-based monitoring provides primary data that enables local and landscape-scale assessment of changes in the riparian plant community relative to changes in annual hydrology.

With the increasing recognition of the role that both vegetation and river regulation have on fluvial geomorphology, studies evaluating the additive effects of these change agents on shoreline and channel geomorphic landforms are increasingly relevant to resource managers interested in preserving or re-establishing channel dynamics and in native plant restoration efforts (Stromberg, 2001). Just as plants respond to river regulation, the location and distribution of riparian plants along a channel affects alluvial landform evolution (Corenblit and others,, 2008; Osterkamp and Hupp, 2010; Manners and others, 2014). In Grand Canyon, the effect of riparian plants on the physical template of the Colorado River corridor is little studied, yet the interaction between vegetation and sediment has implications for campsite availability and accessibility (Hadley, 2014, Kaplinski and others, 2005, 2014), wildlife habitat (Durst and others, 2008; Sogge and others, 2003), and aquatic shoreline habitats.

Table 1. Description of Plant Response-guild and associated species within guilds.		
Guild	**Guild Description**	**Species**
A	Xeroriparian shrubs, disturbance intolerance	*Lycium pallida, Artemisia ludoviciana, Baccharis sarothroides*
B	Drought tolerant well dispersed, ruderal herbs/grasses	*Melilotus* spp., *Oenothera pallida, Bromus rubens, Sporobolus cryptandrus*
C	Mesic, well dispersed, herbs/grasses	*Taraxicum officianale, Conyza canadensis*
D	Wetland, clonal grasses	*Agrostis stolonifera, Phragmites australis*
E	Wetland, low growing, short-lived, forbs	*Equisetum arvense, Veronica americana*
F	Wetland, shallow rooted, forb, nonclonal	*Apocynum canabinum, Boehmeria cylindrica*
G	Wetland, perennial grasses, forbs	*Juncus* spp. *Muhlenbergia asperifolia, Typha latifolia*
H	Tall-deep rooted, disturbance tolerant riparian phraeatophytes	*Tamarix* spp., *Salix exigua, Pluchea sericea*
I	Woody, xeroriparian, disturbance adapted	*Prosopis glandulosa, Celtis reticulate, Acacia greggii*

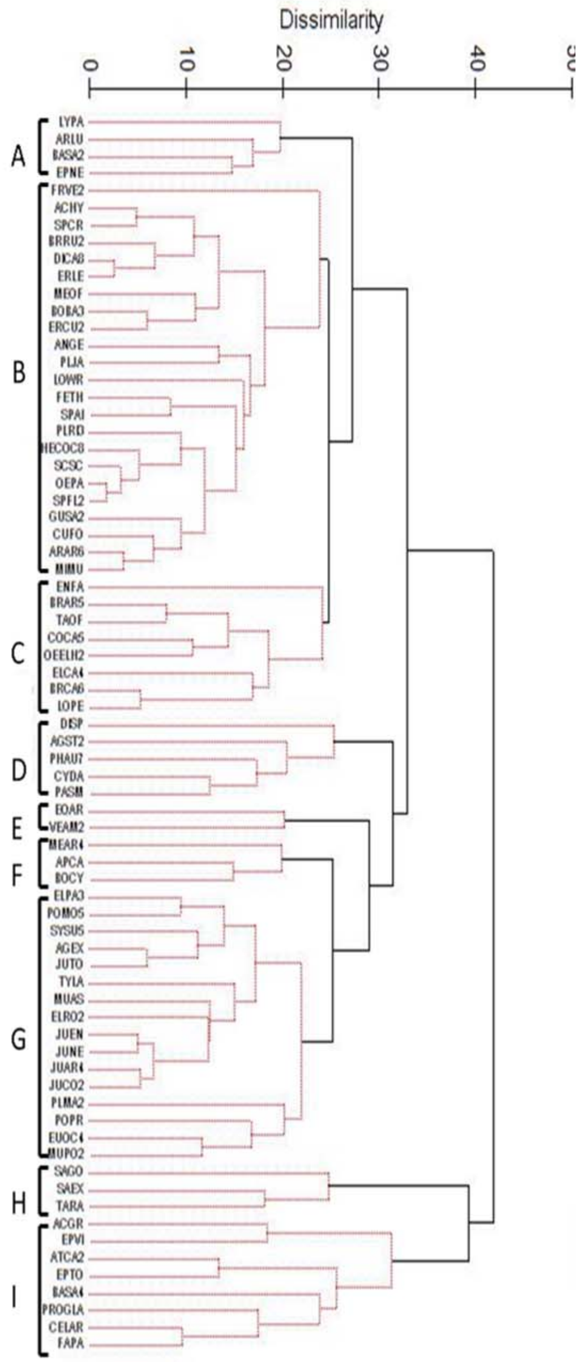

Figure 1. Dendrogram of preliminary Plant-response guilds for the Colorado River in Grand Canyon.

The plant response-guild information developed during FY13–14 provides a means to aggregate multiple species into a single variable (guild) to study vegetation's effect on sediment dynamics. For example, each response-guild, composed of a suite of species, could be assigned a single roughness value when considering the process of sediment transport and deposition, or a single critical shear stress value assigned to a response-guild to evaluate plant removal and erosion during high flows in Grand Canyon. A research element for FY15–17 proposes to conduct a retrospective analysis of sandbar evolution since 1991 when significant flow regime changes occurred. A retrospective analysis of sandbar evolution contributes to an understanding of how landforms along the channel change in response to annual hydrology, controlled floods, and the presence of vegetation.

Riparian vegetation comprises critical habitat for terrestrial fauna along the Colorado River corridor (Carothers and Brown, 1991; Kearsley and others, 2006; Ralston, 2005), yet the relationship between riparian guilds and these animal species remains unstudied. While dam operations modify the frequency of vegetation guilds likely leading to changes in the abundance and distribution of animal species that rely on these habitats, most studies of terrestrial consumers were done many years ago over a relatively short period of time. During these shorter time scales, the primary linkage between flow regime and terrestrial animals may be through variation in space and time in the amount of emerging aquatic insects that are available as prey to terrestrial consumers. Therefore, we will study a suite of terrestrial consumers to better understand short-term variation attributable to changes in the strength of insect emergence from the Colorado River and, where long-term data are available, use methods that allow us to make inferences about long-term changes potentially linked to vegetation change. To the extent possible, we will also use historic data to better understand which animal species are linked to specific vegetation-flow response guilds

Lastly, native and nonnative woody riparian vegetation expansion is linked to Glen Canyon Dam operations (Turner and Karpiskac, 1980; Mortenson and others, 2011), but removal of woody vegetation through dam operations may have limited success. To achieve desired future conditions for riparian vegetation, experimental vegetation removal and plantings of native vegetation that incorporate future flow operations may be required. For example, experimental plant removal and subsequent habitat restoration efforts may focus on tamarisk since tamarisk beetle defoliation has occurred along segments of the Colorado River since 2009 (see Project Element 11.2). Incorporating a review of previous riparian restoration projects within the Colorado River Basin (Colorado River in Canyonlands, the Yampa River in Lodore Canyon, and the Rio Grande River in Big Bend National Park) can identify approaches that may be most successful in identifying expected outcomes, and in estimating costs for project initiation and subsequent monitoring and maintenance. Project Element 11.5 proposes a science panel review to examine successes and challenges in non-native vegetation control in the Colorado River and Rio Grande watersheds (the area that is the jurisdiction of the US and LC regions of reclamation) and to seek recommendations from that group as to how to plan a scientifically-based riparian management control program.

Collectively, the monitoring and research elements proposed in the riparian vegetation project support the Adaptive Management Program's efforts to evaluate the High-Flow Experiment Protocol (Bureau of Reclamation, 2011) and flow alternatives that will result from the on-going EIS for a Long-term Experimental Management Plan (LTEMP) for Glen Canyon Dam. The proposed research elements fundamentally aid in furthering our understanding of the role of riparian vegetation in ecosystem processes of a regulated river.

C.1. Scientific Background

A riparian plant community integrates the history of hydrologic events that vary in magnitude of disturbance and depth of inundation (Naiman and others, 2005). General conclusions from decades of plant studies along the Colorado River downstream from Glen Canyon Dam and in other rivers in the southwest are:

- tamarisk colonization events occur following large-scale disturbance that create bare substrate for colonization, or changes in the flow regime of regulated rivers where alluvial deposits become exposed (Stevens and Waring, 1986; Birkin and Cooper, 2006; Mortenson and others, 2012);
- the reduction in magnitude and frequency of floods in Grand Canyon promoted the development of marsh communities (Stevens and others, 1995);
- woody riparian vegetation, in general, has expanded under Record of Decision (RoD) operations also because of reduced flood magnitude and disturbance (Sankey and others, unpublished).
- increases in base flow in the mid-2000's resulted in increased woody vegetation expansion below the stage of 25,000 ft^3/s discharge even with increasing flood frequency (Sankey and others, unpublished).

Landscape scale research and small-scale data collection since the 1980s document the immediate and long-term response of vegetation to changes in seasonal hydrographs and minimum base flows associated with dam operations.

Current knowledge gained from geophysical studies affords opportunities for linkages between geomorphology and plant ecology to assess the interactive response of sediment and vegetation on landform processes and terrestrial habitat quality. Key insights from the physical science program for the Colorado River in Grand Canyon that are fundamental to integrated research include the following:

- Sediment grain-sized eddy bars and channel margin deposits has coarsened since Glen Canyon Dam was completed; wind-transported deposits are also coarser as a result (Draut and others, 2008; Schmidt and others, 2004; Topping and others, 2000a, b).
- Sandbar response to high-flows include deposition occurring principally within debris fan eddy-complexes, with the greatest amount of deposition occurring near zones of flow separation and reattachment (Hazel and others, 1999; Schmidt and others, 2001); Sediment storage along the channel is greatest within these eddy complexes (Hazel and others, 2006b).

Coarser sediment deposits along the river's channel and upslope have implications for water accessibility and nutrient availability to the roots of plants. Coarser sediments and reduced nutrient availability favor drought tolerant plant species and plant species that are adapted to nutrient poor environments. Controlled floods result in sediment reworking and deposition, and affects vegetation by scouring herbaceous vegetation and partially burying woody vegetation (Kearsley and Ayers, 1999). Vegetation that is adapted to burial or disturbance (for example, *Salix exigua*, *Pluchea sericea*; table 1) may fair better under increased frequencies of controlled floods. Sediment deposition that results in sandbars with increasing elevation affects relationships plants roots have to the water table. Plants that are more drought tolerant and have deeper root systems may be favored under this scenario (for example, *Prosopis* sp., *Tamarix* sp.; table 1).

The vegetated landscape that results from changes in sediment characteristics and landform evolution affects associated terrestrial fauna. Sogge and others, (1998) identified that complex structural habitat, present along the river channel from 1990-1994 increase bird diversity. A long-term trend towards increased woody vegetation of similar architecture and height may result in either reduced bird diversity, or the attraction of a different assemblage of birds than those currently observed along the channel. Similarly, the terrestrial arthropod assemblage that forms a food base for both terrestrial and aquatic species may change as substrates become drier, or vegetation shifts from a mix of perennial herbaceous and woody vegetation towards a predominantly woody vegetated landscape (McCluny and Sabo, 2012; Paetzold and others, 2008). Whereas vegetation may act a primary filter to determine which species are present in a given area, the abundance and distribution of particular terrestrial animal species may also be affected by the amount of local insect emergence (Project 5).

The physical components that are studied downstream of Glen Canyon Dam (Projects 2, 3) constitute the abiotic inputs that constrain landform processes and the biotic responses. Understanding the riparian landscape response to Glen Canyon Dam operations requires collective analysis of data from physical and biological disciplines. The challenge for the FY15–17 Project 11 work plan is higher-level research that links physical and biological responses and associated feedbacks. The proposed research elements fundamentally aid in furthering our understanding of the role of riparian vegetation in ecosystem processes and the potential effect of riparian vegetation on habitat quality within a regulated river.

C.2. Management Background

Vegetation is recognized as in important element of the Colorado River and is highlighted with a specific management goal [Goal 6: Protect or improve the biotic riparian and spring communities, including threatened and endangered species and their critical habitat] of the GCDAMP. Vegetation provides wildlife habitat (cover, forage, nesting), is the basis of terrestrial food webs, influences channel and bar dynamics, provides recreational opportunities and aesthetic value, and performs many of the important functions and services valued by humans. Most recently, the response of vegetation to future flow regimes associated with the LTEMP EIS has been a focus for stakeholders. The vegetation component of the EIS process considers how groups of riparian plants may respond to changes in flows and how particular flow regimes may benefit native or nonnative species (for example, tamarisk), increase biodiversity, and affect the Desire Future Conditions developed by stakeholders. The State and Transition Modeling effort by Ralston and others (2014) provided stakeholders with a tool that can assist in evaluating how plants respond to changes in the flow regime. For example, the state and transition models suggest that relying of flows to remove woody vegetation is likely to have limited success, unless the flow regime includes large extended controlled floods like those that occurred in the mid-1980s. These collaborative efforts between the GCMRC, the LTEMP EIS team and the agency leads involved in assessing alternative flow regimes provides opportunities to be forward thinking about the need for mitigation efforts related to vegetation management, as a means to support goals for vegetation associated with desired future conditions for the Colorado River downstream of Glen Canyon Dam. The state and transition model provides a first step in being aware of potential vegetation management needs, strategic planning for vegetation management that is linked to monitoring and research outcomes can be a follow-up step.

Monitoring approaches have aimed to collect data in a manner that informs stakeholders of the status of riparian vegetation as well as other elements of the riparian ecosystem (Kearsley and others, 2006; Ralston and others, 2008). The response of riparian vegetation to dam operations can positively or negatively affect the quality of other resources within the riparian zone. For example, available campable area can decline as vegetation cover increases (Kearsley and others, 1994), though more recent analysis suggests that since 2002 vegetation encroachment in campsite areas appears to be less important when evaluating changes in campsite conditions (Hadley, 2014). Additionally, though not well documented in Grand Canyon, increasing vegetation on sandbars likely affects sediment transport dynamics and aeolian processes thus playing a role in sediment conservation (Trimble 2004, Kean and Smith, 2004; Dean and others, 2011; Draut and Rubin, 2008). Thus, the status of riparian vegetation and its relationship to other resources is a primary information need for the stakeholders to evaluate how dam operations are affecting downstream resources.

This project consists of monitoring and associated research activities relating to the measurement of riparian vegetation attributes in response to dam operations to inform multiple stakeholder needs. Project 11 incorporates information gained from previous monitoring efforts (Stevens and Ayers 1995; Kearsley and Ayers 1995; Kearsley and others, 2006) and recommendations from protocol review panels (Urquhart and others, 2000; Cooper and others, 2008). The primary objectives of this project are to measure variables of plant response (cover, species presence, and abundance) as related to the geomorphic setting, elevation, and flow regime. These variables inform stakeholders about the status of vegetation and support analysis of vegetation's role in the physical and sociocultural responses to dam operations. The proposed methods in the Plant-response Guild element also support research related to evaluation of alternative flow regimes, including implementation of the High-Flow Experiment Protocol (U.S. Department of the Interior, 2011) and other flow regimes that may result from the LTEMP EIS. The sampling is hydrologically and geomorphically based, the annual sampling schedule in September and October generally brackets proposed high flow releases, and sampling at the end of each growing season provides an assessment of riparian vegetation for each year. Thus, data collected by this project contribute to core monitoring, agency actions such as the High-Flow Experiment Protocol or other dam operations, and fundamental support for understanding riparian plant responses within a regulated river.

C.3. Key Monitoring and Research Questions Addressed in this project

This project addresses the following Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) and Desire Future Conditions (DFC's) previously identified by the GCDAMP.

Primary SSQs addressed are:

- **SSQ 2-1.** Do dam-controlled flows affect (increase or decrease) rates of erosion and vegetation growth at archaeological sites and TCP sites, and if so, how?
- **SSQ 5-7.** How do warmer releases affect viability and productivity of native/nonnative vegetation?

The primary information needs addressed by these projects are CMINs 6.1.1., 6.2.1, 6.5.1, and 6.6.1, which are summarized as the following:

- Determine and track the abundance, composition, distribution, and area of terrestrial native and nonnative vegetation species in the CRe
- Determine parameters and metrics to be measured, and the information needs that address each element
- Determine how the abundance, composition, and distribution of the Old High Water Zone, New High Water Zone, and sand beach community have changed since dam closure (1963), high flows (1984), interim flows (1991), and the implementation of ROD operations (RIN 6.2.1, 6.3.1, 6.4.1, 6.5.1, 6.5.2, 6.5.3)

In addition to supporting GCDAMP Goal 6, this project also supports Goals 8, 9, and 11.

- **Goal 8:** Maintain or attain levels of sediment storage within the main channel and along shorelines to achieve GCDAMP ecosystem goals.

This project supports Goal 8 by collecting vegetation response data associated with sandbars and other geomorphic features that physical scientists can use to further understand mechanisms affecting sediment storage and transport.

- **Goal 9**: Maintain or improve the quality of recreational experiences for users of the CRe within the framework of GCDAMP ecosystem goals.

This project supports Goal 9 by collecting vegetation response data that may inform researchers about how vegetation cover and abundance affects recreational experiences. This has implications for both direct vegetation management as well as altering flow regimes to achieve specific management goals.

- **Goal 11:** Preserve, protect, manage, and treat cultural resources for the inspiration and benefit of past, present, and future generations.

This project supports Goal 11 by collecting vegetation cover data and an overall species list that may be used to inform other researchers about how the quantity of vegetation affects sediment transport and cultural site preservation, or how the loss or gain of plant species affect interpretations of ecosystem status.

All element of this project also support information related to the Desire Future Conditions (Department of Interior, 2012) associated with: *Sediment-related Resources*, the *Riparian Domain* and the Linkages component - *Ecosystem Structure*. The research

D. Proposed Work

D.1. Project Elements

Project Element 11.1. Ground-based Vegetation Monitoring

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Daniel Sarr, Research Ecologist, USGS, GCMRC
Emily Palmquist, Ecologist, USGS, GCMRC
Todd Chaudhry, Restoration Ecologist, NPS, Grand Canyon National Park,
Dustin W. Perkins, Program Manager, NPS, Northern Colorado Plateau Inventory and Monitoring Program

Work Category: Required monitoring

Objectives

- To annually collect vegetation data (presence, cover) within a geomorphic and hydrologic framework downstream of Glen Canyon Dam.
- To use the traits of the plants found to identify plant response-guilds
- Data and results are collected and described in a manner that can be utilized by multiple stakeholders for monitoring approaches used by Tribal stakeholders, and for use in basin-wide riparian vegetation monitoring programs overseen by the National Park Service's Northern Colorado Plateau Network Inventory and Monitoring Program

Hypotheses/Questions

1. Tracking response guild frequency as determined through annual data collection is an effective way to monitor directional responses of the riparian community and the river channel to dam operations.

Rationale/Justification

River regulation in the semi-arid West creates conditions that support both nonnative and native riparian plant species (Stromberg, 1998; Rood and others, 2009). The altered flow regime associated with river regulation can promote successful colonization of nonnative species, particularly tamarisk (*Tamarix* spp.) or other colonizing species, on newly exposed bare substrates (Sher and others, 2000; Birken and Cooper, 2006; Mortenson and others, 2012). In the southwest, the riparian plant community is one in which nonnative tamarisk or Russian olive dominates the landscape (Friedman and others, 2005). Consistent monitoring at the local and landscape scale, and research that strives to understand the interplay among river regulation, riparian vegetation response and the feedback between riparian vegetation development and sediment deposition in regulated rivers is critical. Ground-based monitoring provides an assessment of annual changes in species occurrences that feeds into the frequency occurrence of response-guilds.

Methods

The study area consists of four river segments whose limits are defined by the influence of tributaries and by floristic communities (Glen Canyon, Marble Canyon, eastern Grand Canyon, western Grand Canyon; fig. 2). The confluences of the Paria and Little Colorado Rivers and Kanab Creek with the Colorado River are points that divide the four segments. These river segment designations also overlap with suspended sediment sampling stations and work focused on sediment budgets that bracket Marble Canyon and eastern Grand Canyon (see Project 2). Further, assessing response guilds within short river reaches can help stakeholders identify areas that may be more or less responsive to dam operations. Species lists obtained from plot sampling (described below) within these river segments can inform park management of areas where undesirable species occur in greater abundance and allow a more focused approach to controlling these species.

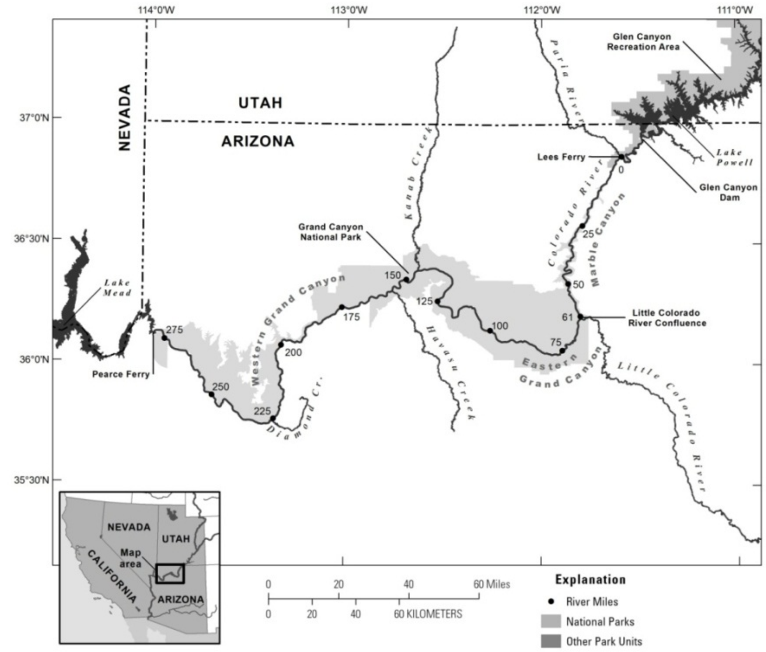

Figure 2. Four landscape-scale segment used for stratification (Glen Canyon, Marble Canyon, Eastern Grand Canyon, and Western Grand Canyon). The confluences of the Paria, and the Little Colorado Rivers, and Kanab Creek with the Colorado River separate the four segments.

Ground-based sampling

Sampling is intended to be complementary with the Big River Protocol of the NPS Northern Colorado Plateau Network (Scott and others, 2011), which includes fixed sites and randomly sampled sites that are matched to geomorphic features (e.g., reattachment bar, separation bar, debris fan, channel margins). Sampling downstream from Glen Canyon Dam will follow a similar approach. Fixed sites will be coincident with sandbar monitoring sites (Hazel and others, 2010, see Project Element 3.1). Random sites will be stratified and equal numbers of geomorphic features other than sandbars will be sampled within river segments. Response guild identification was initiated in 2012 in collaboration with D. Merritt using species lists and data collected from 2001-2005 (Kearsley and others, 2006) and Stevens and others, (1995) from 1991-1993 and data collected in 2012. These guilds continue to being refined as monitoring data are added to the database.

Common to all sites is the division of the site into hydrologic zones for plot sampling. Plots at fixed and random sites will consist of 1-m^2 plots placed along a transect perpendicular to the channel (fig. 3*A)*. A minimum of three transects will be sampled at each site (larger sample sites will have up to five transects). Each transect is divided into three hydrologic zones that correspond to Record of Decision Operations. The active channel (AC) is the portion of the channel feature that is subject to daily fluctuations up to 25,000 ft^3/s. The active floodplain (AF) is that area within a sampling unit that is subject to periodic inundation associated with either steady discharges above 25,000 ft^3/s or experimental floods with discharges up to 45,000 ft^3/s. The elevation above the 45,000 ft^3/s stage is considered the inactive floodplain (IF) which has not been inundated since the late 1980's. Within each hydrologic zone, three evenly spaced plot locations will be established (fig. 3B).

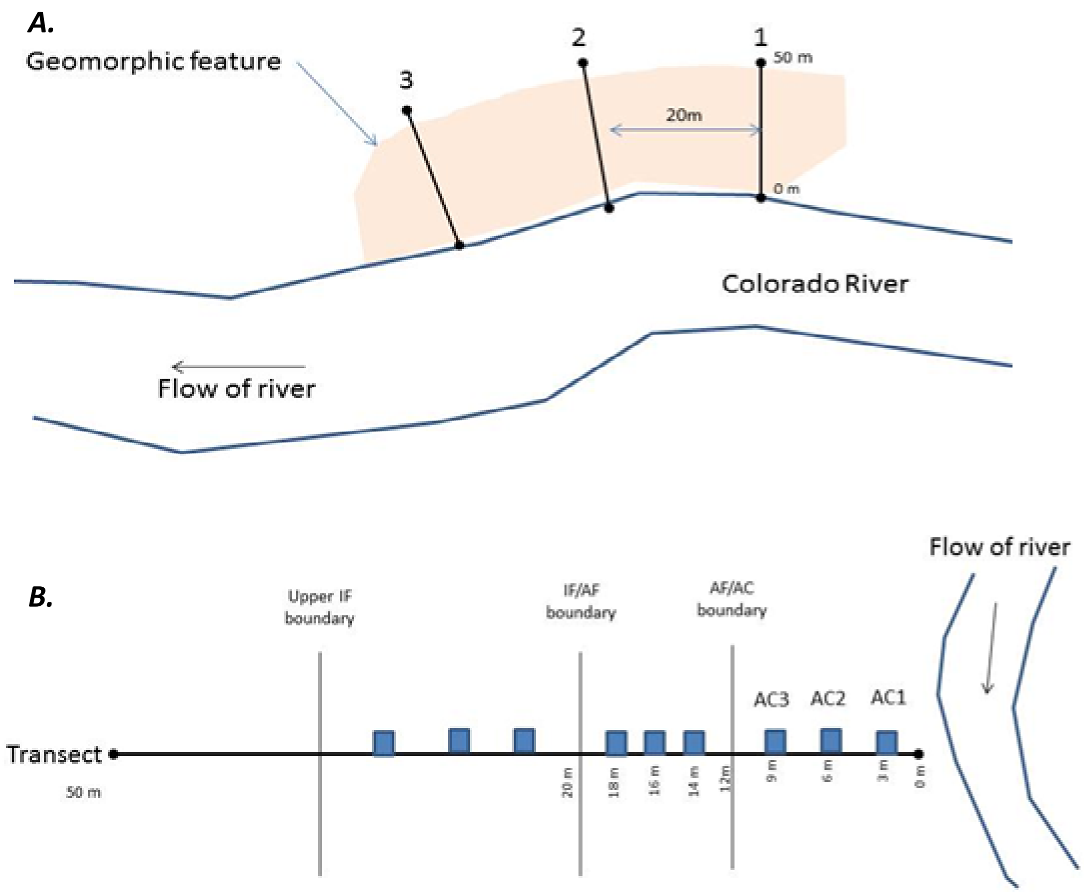

Figure 3. Example of transect lines across a feature (*A.*) and example of hydrologic zone differentiation and evenly space plot placement within zones (*B.*).

For each plot, every species within each plot is identified and the percent vegetative cover for each is estimated using a 1 m^2 frame with 0.1 m segments marked on it. Cover estimate to the nearest 5% (e.g. 5%, 10%, 15%), except for cover values of less than 5%. For cover <5%, record "T" for trace if cover is less than 1% and record 1% for cover between 1% and 5%. We will also estimate ground cover elements: bare soil surface, litter, woody litter (>5 mm diameter), biological soil crust, gravel (5 mm – 7.5cm), stone (25 cm – 60 cm), boulder (>60 cm), bedrock, and water, but only those areas not covered by plants (see data sheet example). The proposed data collection and basic metrics calculated appear in table 1. Plot data will also provide species richness and diversity and distinguish between native and nonnative species

Fixed site sampling

Sampling sites are coincident with sandbar and channel monitoring sites. Among the potential sites that can be sampled (44 sandbars and the river channel data from RM 30 to 87), sandbar sites that are most and least responsive to controlled floods, as measured by changes in sand volume and area (Hazel and others, 2010; Schmidt and Grams, 2011). Because the 44 sites in Project 3 are surveyed and sandbar area and volume calculated, the relationship between vegetation plot locations, associated plant response guild (derived from plot samples) and stage can be determined. Monitoring vegetation response guilds at sandbars that are measured for responses to HFEs and other dam operations can help address physical resource questions about causes of variability in sandbar response. Specifically, this co-located data collection effort can support the monitoring and research questions presented in Project 3 with respect to the role of vegetation and the type of vegetation present on a sandbar affecting sandbar response to controlled floods.

Plots at fixed sites will consist of 1-m^2 quadrats that are stratified across across the survey area (*sensu* Schmidt and Rubin, 1995). The number of quadrats sampled will be proportional to the area of each feature. For example, a reattachment bar may be half the size of a separation bar and would have 50% fewer plots sampled. Plots will be randomly placed within each geomorphic feature. Because the sandbar sites are surveyed annually (Project 3), the topographic information can be used to determine river flow necessary to inundate plots. The complementary data reduces the time necessary to locate permanent plots and obviates the need to monument plots. The vegetation monitoring determines annual changes in response guilds to dam operations and informs managers about how these changes may affect geomorphic features. Data collected will include cover and species presence. Plot data will also provide species richness and diversity and distinguish between native and nonnative species (table 2).

Random site sampling

The objective of random site sampling is to augment the fixed site sampling. Plot sampling here is limited to the area affected by annual dam operations including HFEs. Sampling includes an equal number of sandbars, debris fans, and channel margins within each river segment. Selection of random sites occurs prior to the sampling trip to ensure the sites are logistically feasible. Because the locations will be determined prior to launch of the trip, the height above river level in relation to the 45,000 ft^3/s stage can be determined using established stage elevation relationships and flow routing models (Griffin and Wiele, 1996; Hazel and others, 2006). Having the known river discharge for a particular day and time of day can assist in determining distance upslope to reach the 45,000 ft^3/s stage. Successive plots along the transect line will be sampled. These results will be compared with the fixed sampling site results for an assessment of the river segment and total river corridor.

Analysis

Sampling occurs annually at the end of the growing season (September/October) to capture vegetation response to changes in the annual flow regime. These sampling approaches will also capture non-flow related interactions (e.g., tamarisk leaf beetle) that affect changes in community composition. Data analyses result in descriptive metrics outlined in Table 2 and are used to support response guilds identification. For many of the common species, the physiological traits that are related to hydrology (disturbance tolerance, inundation capacity, drought tolerance), reproductive mode (seed only, vegetative), growth form, life span and salinity tolerance are determined for species encountered, primarily from the PLANTS database (www.usda.gov). These traits are used in a classification procedure to statistically determine the plant-response guilds (fig. 1). The number of species within each guild and the number of guilds may change as more trait information is quantified and added.

Table 2. Data collected for all plots and interpretation

Objective	Data			Inference Goal	
	Raw	Summarized		Trend	Statistic(s) for status
Estimate temporal change in riparian and wetland plant communities	Herbaceous spp			Y*	$\bar{x}$ % cover/sp; p plots/sp
		spp richness		Y	$\bar{x}$ richness
		Total herbaceous		Y	$\bar{x}$ % cover
	Woody spp			Y*	$\bar{x}$ % cover/sp; p plots/sp; $\bar{x}$ no./m^2
		Total woody		Y	$\bar{x}$ % cover; p plots; $\bar{x}$ no./m^2
	Exotic spp			Y*	$\bar{x}$ % cover/sp; p plots/sp
		spp richness		Y	$\bar{x}$ richness
		Total exotics		Y	$\bar{x}$ % cover; p plots
	Litter			Y	$\bar{x}$ % cover
	Bare ground			Y	$\bar{x}$ % cover

Timeline

Work and reporting schedule.

	FY 15	FY 16	FY 17
Field work	September, October	August, October	August, October
Meeting w/NPS, Tribes	February	February	February
Draft Report	May	May	May
Final Annual Report	December	December	December

Outcomes and Products

- Annual species list provide at annual reporting meeting
- Annual monitoring report describing changes in cover and species occurrence along the river corridor. Description of changes in indicator species and changes in frequency of vegetation response-guilds. – As an annual report this may be folded into a USGS data series report where data are accessible to the public and each year's data are added to the report, FY 15, 16, 17.

- USGS Methods and Techniques report formalizing sampling to be reviewed by statisticians and ecologists FY15.
- Peer-review journal articles on response-guilds as a monitoring tool for rivers in the southwestern United States. One identifying guilds within Grand Canyon and among other rivers of the Colorado River Basin.

Project Element 11.2. Periodic landscape scale vegetation mapping and analysis using Remotely Sensed Data

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Barbara Ralston, Supervisory Biologist, USGS, GCMRC
Daniel Sarr, Research Ecologist, USGS, GCMRC

Work Category: Required monitoring

Objectives

1. To produce an accurate classification of vegetation from the imagery acquired with the remote sensing overflight in 2013.
2. To quantify stability and changes in vegetation composition from the classifications of vegetation completed for imagery acquired in 2002 to 2013.
3. To cross-walk the composition of vegetation in the image-based classes from 2013 and 2002 with composition of response guilds identified in Element 11.1.
4. To detect and map tamarisk leaf beetle effects for remotely sensed vegetation canopies from overflight imagery from 2009 to 2013.

Hypotheses/Questions

1. *What was the composition of riparian vegetation in 2013, and how did it vary spatially throughout the CRe?*

The ability to address the first question of this objective is contingent upon successful, accurate classification of vegetation based on the 2013 imagery that is as good as or better than the classification based on 2002 imagery. The classification will be derived from the high resolution (20-cm pixel size) multispectral remote sensing imagery from the May, 2013 overflight for the entire river corridor of the CRe. This will produce a new and up-to-date assessment of the presence, absence, and composition of vegetation in the CRe. (This work will be completed by Laura Cagney).

2. *How has the vegetation composition in the CRe changed within the approximately 1-decade period from 2002 to 2013?*

The assessment of change and stability in vegetation composition will span a decade of river-management characterized by reduced powerplant operations and 3 controlled floods, as well as the appearance of the tamarisk leaf-beetle (*Diorhabda carinulata*) in portions of the CRe. Importantly, the 2013 classification can also be added to the long term assessment of riparian vegetation encroachment for select reaches (Waring, 1995) of total vegetation from 1965 to 2013 that was successfully completed using data through 2009 in the FY-14–15 work plan. We anticipate that changes from 2002 to 2013 will reflect a suite of environmental conditions identified by previous work at GCMRC; including recent work completed during the FY 13–14 work plan. Based on previous work, we hypothesize that (i) temporal stability and changes in vegetation classes (composition) will vary by river stage zone, and (ii) compositional changes by river stage zone will be indicative of effects of regional drought at higher elevations, and river hydrology (e.g., flow duration) at lower elevations. Moreover, we know from work completed during the FY13–14 work plan that the long-term, post-dam trajectory of increased vegetation expansion into increasingly lower elevation zones occurred during the 2002 to 2009 time period at elevations well below the maximum of recent controlled floods. Therefore, we will ask whether increases and decreases in vegetation at these lower elevations (i.e., inundated during operations that include controlled floods between 2002 and 2013) vary by vegetation class composition. In particular, we will focus on identifying the range of (and most common) classes of vegetation that bare ground (e.g., sand) transitioned to from 2002 to 2013. Finally, we know that the tamarisk leaf beetle appeared in portions of the CRe during the time period of our vegetation composition change analysis and therefore we will ask whether the spatial variability in changes in the abundance of the class containing tamarisk exists and if so, whether it correlates to understanding of where the tamarisk leaf-beetle existed pre-2013? (This work will be completed by Laura Cagney in collaboration with Joel Sankey).

3. *Can the composition of vegetation in the image-based classes from 2013 and 2002 be cross-walked with the composition of response guilds identified in Element 11.1 in a manner that produces a useful and accurate, landscape-scale assessment of spatial variability in response guilds?*

To the extent possible, we will expand on the third question to quantify how the relative abundance and spatial variability in the detectable response guild(s) have and have not changed during the approximately 1-decade time period. Our ability to detect these changes, if present, largely depends on whether the composition of response guilds can be effectively cross-walked. (This work will be completed by Joel Sankey in collaboration with Barbara Ralston and Daniel Sarr).

4. *Can beetle-impacted stands of tamarisk be detected and successfully mapped by independent and combined analysis of 2009 and 2013 imagery in select reaches where the leaf beetle are known to have appeared since approximately 2009. Additionally, can variability and changes in remotely sensed characteristics of the tamarisk canopies (e.g., greenness, cover, leaf area) be detected and attributed quantitatively to the presence of the leaf beetle?*

This fourth question will focus on specific reaches where the beetle appeared since 2009, including (1) Kanab Creek in Grand Canyon, (2) within Glen Canyon, as well as (3) a control reach not yet impacted by the leaf beetle. (Completed by NAU M.S. student Ashton Bedford with Joel Sankey and Barbara Ralston serving as thesis committee members).

Rationale/Justification

The relative abundance and composition of vegetated and non-vegetated surfaces are factors that contribute to the evaluation by stakeholders of goals for physical resources, recreation, cultural resources, and riparian communities. In addition to producing a basemap of vegetation composition and providing additional data for detection and analysis of stability and change, mapping vegetation at the landscape scale can inform stakeholders of the status of several resources in the CRe that include: effects of riparian vegetation for campsite quality (Kearsley and other, 1994; Hadley, unpublished); and effects of riparian vegetation for wildlife habitat (Kearsley and others, 2006; Sogge and others, 2003); effects of riparian vegetation on transport of sand along the fluvial-aeolian-hillslope continuum, which is important to archaeological site preservation (Draut and Rubin, 2008). The development and application of a remote sensing image-based methodology that is accurate and provides a synoptic assessment of the CRe has been identified as integral to supplementing and corroborating ground-based monitoring data.

The primary deliverable product is a vegetation classification dataset that can be used in multiple disciplines working in the CRe, with additional deliverables focused on salient interpretations of variability and change in vegetation composition summarized in written report(s) and journal manuscript(s). The dataset will extend from the 8,000 ft^3/s to 250,000 ft^3/s shoreline, starting at River Mile -15 and ending at approximately River Mile 280. The products are designed to fulfill stakeholders' request to, "Determine and track the abundance, composition, distribution, and area of terrestrial native and nonnative vegetation species in the CRe." as defined by Core Monitoring Information Needs (CMIN) 6.1.1., 6.6.1., 6.2.1, 6.5.1.

Methods - Preparation of 2013 imagery mosaic and shoreline masks

Before vegetation analysis can begin, the 2013 imagery must be mosaicked from flight lines received from the contractor, and broken down into standardized GCMRC Quarter-Quarter-Quad boundaries. This process includes the required reflectance value or digital number histogram matching. Another critical step before vegetation analysis can begin is to produce a shoreline, which also creates the ability to remove known open water pixels from further analysis. Depending on the sediment load of the 2013 imagery, this process can be executed using a Green/Red band ratio extraction or a principal component analysis approach. The Green/Red band ratio extraction compares the values of the green band to the red band. These two reflectance values are uniquely different when trying to isolate open terrestrial water and will result in a dataset that represents the May 2013 shoreline at a steady 8,000 ft^3/s water discharge.

Methods - Total vegetation map

We will produce a total vegetation database and a vegetation class database with at least 6 vegetation classes for the entire river corridor up to the top of the Old High-Water Zone (at the 250,000 ft^3/s flow stage) using image processing of remotely sensed data. Normalized Difference Vegetation Index (NDVI) is a commonly used method to segregate total vegetation in multispectral data. A more robust and accurate method is the Spectral Angle Mapper (SAM), which was used in mapping with the 2009 imagery and is proposed for use with the 2013 dataset. The SAM technique provides the vector angle between the wavelength-band values of an image pixel determined to be vegetation. For any pixel, the smaller the vector angle, the more likely the image pixel is to contain vegetation. Both sunlit and shadowed vegetation spectra will be used in the SAM analysis in order to map all vegetation, even within shadows. If image band data are consistent throughout the corridor, then the range of SAM values for vegetation should also be consistent, or at least vary systematically throughout the canyon, allowing the vegetation to be mapped quickly. The range of SAM values for vegetation will be determined interactively using the image result from the SAM output and the corresponding color-infrared image. To determine corridor consistence and variability, SAM ranges will be determined every 8 km of the corridor;

if the derived SAM ranges are consistent or vary systematically, then the observed SAM range relation will be used to map the total vegetation throughout the canyon. The results for each of the 126 image tiles that cover the river corridor will be examined for accuracy and the SAM range adjusted when necessary. If the initial SAM ranges at 8 km increments are random, then the SAM range for every image tile will be independently determined and applied interactively to provide an accurate total vegetation database.

Methods - Vegetation classification

Once total vegetation is segregated in the 2013 image data set (anticipated by or before summer 2016), a most-likely vegetation species will be assigned to each image pixel based on reflectance angle. Even though final mapping will probably occur at the response guild or association level (categories of classification within the National Vegetation Classification Standard (FGDC, 2008)), the spectral band quality of the 2013 imagery are very different in terms of dynamic range, consistency, and accuracy and, therefore, the level of the final vegetation map for this database will not be known until the species classification is completed. Species classification will be accomplished using the following information, in order of preference: (1) ground observations that were collected in August and September 2013; (2) ground-truth site observations that occurred during other image acquisitions, where it is determined by visual examination of the periodic images that certain vegetation is the same in the image data being analyzed; and (3) our previously collected ground-reflectance database for the common vegetation species within the canyon. Image classification will proceed in 8-km increments progressing downstream in the river corridor from Glen Canyon Dam, because vegetation composition and the spectral properties of species gradually change downstream.

Image classification will be based mostly on the image-band signatures and canopy texture of representative vegetation species (Davis and others, 2002). Species classification using the 2013 image data will use a supervised classifier, such as Maximum Likelihood, SAM, or Neural Network. We will experiment with various classifiers to determine the classifier that is most robust and produces the highest accuracies for most vegetation species. We will use the same canopy texture measures that were employed for the 2002 vegetation mapping, although the areal dimensions of the spatial tools may change due to the higher spatial resolutions of the 2013 image data compared to that of the 2002 image data, the most recent vegetation map from GCMRC.

Undoubtedly, there will be ambiguities in the final species classifications, because the spectral and textural characteristics of some species overlap. We will try to reduce the ambiguity using knowledge of dominant species within particular ecotones related to river stages, although care will be exercised within the riparian zone not to exclude xeric species. When the species classification process reaches the point of diminishing returns, a statistical accuracy assessment will be performed on the 2013 results, and a determination will be made as to the aggregation levels for their final vegetation databases. We will also incorporate approaches used in Grand Canyon National Park's vegetation-mapping project to develop compatible layers and classes of vegetation.

Methods – Objective 2

Total vegetation from 2013 will be used to extend the long-term change analysis conducted for the FY13–14 BWP using the GIS and statistical methods previously developed and described. Change and stability in vegetation classes from 2002 to 2013 will be summarized by stage-elevation zone, and by units of debris fan, channel margin, and eddy areas as represented in the canyon-wide geomorphic base map (see Project Element 3.1.2). Relationships of temporal variability in vegetation composition by elevation zone and by geomorphic unit will be examined relative to variability in flow duration by elevation zone and the expected response to regional drought from 2002 to 2013. Changes to the abundance and spatial distribution of the class containing tamarisk will be examined longitudinally throughout the corridor and tested for significant differences between reaches where leaf beetles have been and have not been documented.

Methods – Objective 3

The composition of the mapped vegetation classes and response guilds will be compared to determine whether any of the response guilds or aggregates of functionally similar guilds can be accurately represented by individual or aggregate vegetation classes. If some classes or aggregates are successfully identified as potential proxies for response guilds, spatial and temporal variability from 2002 to 2013 will be examined using the change detection and summary methods described for the secondary objective.

Methods – Objective 4

Supervised classification methods will be used to map foliated tamarisk within the study reaches using 2009 and 2013 imagery. The classifications will potentially incorporate the 4 multispectral bands from the imagery in addition to NDVI, EVI and leaf area index (LAI). The classification will be developed from training pixels in the study reaches that represent foliated tamarisk stands. Change analysis of the area mapped as foliated tamarisk in 2009 and 2013 will be conducted. Change analysis will also consider relative changes in the indices (NDVI, EVI, LAI) for locations where foliated tamarisk was mapped as present in one image date and absent in the other, as well as present or absent in both dates. Ground-based point observations of known beetle populations (personal communication, Levi Jameson and Charles van Riper, April 2014, to Ashton Bedford) will be used identify the relationship between changes in presence and remotely sensed canopy characteristics of tamarisk stands and beetle populations.

Outcomes and Products

The primary deliverable is the vegetation classification dataset that will extend from the 8,000 ft^3/s to 250,000 ft^3/s shoreline starting at River Mile 15 and end at approximately River Mile 280, and that can be used in multiple disciplines working in the CRe. Additional deliverables will be USGS professional reports or journal manuscripts that focus on salient interpretations of variability and change in vegetation composition, and at least one publication will be produced per objective by FY17.

Project Element 11.3 Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991 (FY15–17)

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Work Category: High priority research

Objectives

To understand the interplay between hydrology, vegetation and sediment dynamics among 20 sandbars for a 23-year period (1991 to 2013) by using long-term sandbar monitoring data, instantaneous discharge record, sediment transport information, intermittent vegetation sampling data, riparian plant response guilds, and aerial and oblique repeat photography.

Hypotheses/Questions

1. *How does establishment of vegetation nearer the channel (below stage at power plant capacity (31,000 ft^3/s) influence sediment deposition on sandbars (net deposition and scour) associated with experimental high flows?*
2. *Does expansion of woody riparian vegetation below stage elevations of power plant capacity (31,000 ft^3/s) and associated sediment response decrease shoreline complexity and negatively affect native fish rearing habitat (backwaters) and riparian habitat (compositional and structural complexity)?*
3. *In a regulated, debris fan-eddy river system does expanded floodplain development on reattachment bars result in smaller eddy circulation zones and with reduced temporary storage capacity, or do river currents fundamentally change and affect sediment storage and transport capacity?*

Rationale/Justification

In Grand Canyon, the effect of riparian plants on the physical template of the Colorado River corridor is little studied, yet the interaction between vegetation and sediment has implications for campsite availability and accessibility, wildlife habitat, and aquatic and shoreline habitats. The shoreward expansion of vegetation along the channel is believe to be caused by reduced frequency and magnitude of floods, a result of Glen Canyon Dam operations (Turner and Karpiscak, 1980; Sankey and others, unpublished). This results in less frequent disturbance of sand deposits and longer intervals between floods, facilitating vegetation establishment. Since 2002, the greatest increase in woody vegetated area is associated with stage elevations less than 31,000 ft^3/s.

The Experimental High Flow Protocol (Bureau of Reclamation, 2011) will increase the frequency of short-duration flood disturbance to the Colorado River with the goal of causing cumulative increase in the size of sandbars. How vegetation responds to the increased frequency of these short flood pulses, and how vegetation response creates a feedback that affects subsequent patterns of sediment deposition is unknown, but could significantly affect the long-term geomorphic response to the high flow protocol. Increased frequency of short-duration floods greater than 31,000 ft^3/s may limit the expansion of woody vegetation and reverse the observed trend of channel narrowing. Conversely, the presence of vegetation may also accelerate the rate of sediment deposition on sandbars. The presence of vegetation along channel margins increases resistance, reduces water velocities and erosive power, increases bank cohesion, and thus affects sediment mobilization, transport, and deposition. This is reflected by the pattern of vegetation on sandbars, which is often distributed in clumped or linear arrangements, with the densest vegetation associated with the annual flood stage (on the Colorado River in Grand Canyon this has been approximately 566 m^3/s since 2000).

Instead of sediment depositing somewhat uniformly across a sandbar, sediment is predicted to accumulate where vegetation reduces water velocity at and around the vegetation associated with the annual flood stage. This will result in an increase of sandbar elevation near the channel (i.e., vegetated levees), but reduced deposition beyond the vegetation boundary. Repeated floods of similar or smaller magnitude may have a ratcheting effect where deposition on sandbars results in steeper sandbar fronts and channel narrowing. At the same time, vegetation on the sandbar may continue to expand and cover the bar's surface, creating a vegetated floodplain and loss or reduction in the size of the eddy boundary. The repeated response may thus limit the effectiveness of these pulse flows, and change the channel shape and width. Currently, work is under way to test hypotheses about how sandbars stabilized by vegetation affect patterns of streamflow and sand deposition in eddies (FY 13–14 Project A.3) using numerical flow models. The modeling work, which is expected to provide results in late 2014, will provide more specific predictions about how established vegetation will affect depositional patterns. Thus, this proposed retrospective analysis of sandbars will complement the work initiated in FY13-14. In this project we will exploit the more than 20-years of sandbar monitoring data (1992-2013), instantaneous discharge records, intermittent vegetation sampling data, repeat photographs, and plant response-guild occurrence probabilities to describe topographic sandbar response, changes in eddy boundaries and vegetation expansion among sandbars since 1992. The frequency of short-duration high flows, a management action intended to promote sediment conservation, is likely to increase in the coming years. Understanding how vegetation responds to this management regime and its effect on sediment deposition and transport provides stakeholders with critical information that they can use to help meet their goals.

Methods

This element has two parts A: retrospective analysis of vegetation change among sandbars in response to flow regimes (FY15-16). B: linking vegetation change and geomorphology, a proof of concept (FY17).

Approach for Part A: The retrospective analysis uses multiple data sources (Table 3). Topographic surfaces from 1991 to 2013 of selected sandbars will be used to compute the elevation changes between each survey for transects across sandbars and following controlled floods. Using plant-response guilds (based on traits associated with water acquisition and fluvial disturbance, but also grouped based on traits that influence hydraulics) and exceedance probabilities associated with the instantaneous discharge record for each year, we will make occurrence probability maps for plant guilds across the sandbar surfaces for each year. The daily repeat photography collected since 1991 (table 3) will be used to verify guild representation. Repeat aerial imagery will be used to estimate canopy cover. The intermittent vegetation sampling data will also be used to determine guild occurrence relative to predicted guilds and support estimated cover values for guilds. This approach will give a time-series of vegetation succession based on annual hydrology that is also coupled with observed sandbar morphologic change. We propose to do this analysis for 20 sandbars distributed throughout the canyon.

Approach for Part B: The linkage between vegetation change and geomorphology will be strengthened with numerical flow modeling. The purpose of the modeling that was initiated in the FY13–14 work plan (Element A.3) and is proposed to continue in FY15-17 in Project 3.3 examines processes by which vegetation-stabilized bar areas affect flow and deposition (see preliminary findings (Alvarez and others 2013, and Project 3.3 description). The modeling proposed in Element A.3 study will be used to establish relations between the vegetation response-guilds and flow parameters such as velocity and shear stress for high flows. Models will be developed using roughness values for vegetation obtained in the literature (Manners and others, 2014; Griffith and others, 2014) and applied to the guilds. For example, roughness for tamarisk or willow that co-occur in a guild (Table 1) may be applied for all plants associated in the guild. The age of guilds will be determined from the vegetation succession time-series process described above. Age of guilds provides a proxy for the stem diameters of vegetation within a guild. This information and canopy cover estimates that can be used to estimate stem stiffness that influence hydraulics and sediment transport in the water column (Griffith and others, 2014; Kean and Smith, 2004). Available velocity profiles and suspended sediment data will also be used in this modeling effort (McDonald and Nelson, 1996; Wright and Kaplinski, 2011). Subsequent year change in sandbar topography can be used to verify expected versus observed sediment response. This approach is proposed as a proof of concept for a subset (2-4) of the 20 sandbars described in the retrospective analysis for vegetation change beginning in FY17. The subset will be distributed upstream and downstream of the Little Colorado River to account for tributary effects on sediment inputs related to sandbar response.

Table 3. Summary of topographic, sediment transport, imagery and vegetation sample data available for sandbars

Data type	Dates collected	Reference
Instantaneous (15 minute interval) discharge at Lees Ferry	1921 to present	Topping and others, 2003
Sediment transport data	1996, 2000, 2004, 2008, 2012, 2013	Webb and others, 1999; Schmidt and others, 2007; Grams and others, 2013
High-precision Topographic surveys (±0.05m ground point precision)	Annually since 1991	Hazel and others, 2008, Kaplinski and others, 2014;
Stage-discharge relations	1990-2005	Hazel and others, 2007
Oblique Imagery	Intermittently since 1991	USGS, unpublished data
Aerial imagery (orthorectified)	2002, 2009, 2013	Davis, 2013, 2012
Vegetation sample plots	1995, 2001-2005, 2012-2013	Kearsley and Ayers, 1995; Kearsley and others, 2006; USGS unpublished data, 2012-13.

Timeline:
Work and reporting schedule.

	FY 15	FY 16	FY 17
1st quarter	Part A: Data Consolidation, Parameter Identification, Initial methodology outlined	Application of methodology to successive bars	Part B: Initiate Proof of concept, Consolidation, Parameter Identification, Initial methodology outlined
2nd quarter	Preliminary analysis for 4 sandbars	Results	Initial analysis of first sandbar
3rd quarter	Status Report	Draft Report/manuscript	Results
4th quarter	Methods Report and initial results	Manuscript submission	Draft report/manuscript

Outcomes and Products

- Analysis of 20 bars for vegetation response to changing flow regimes.
- Report of 20 sandbars retrospective analyses FY16
- American Geophysical Union presentation FY16
- Manuscripts FY16 – Methods for using response guilds to understand multi-year vegetation response to river regulation: Vegetation assembly rules along a regulated river.
- Draft manuscript FY17 - Twenty-year reconstructive geomorphic history and vegetatitive evolution for 2 sandbars in Grand Canyon.

Project Element 11.4 Linking dam operations to changes in riparian biodiversity – the potential significance of vegetation change and insect emergence

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Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Daniel A. Sarr, Research Ecologist, USGS, GCMRC
Emily Palmquist, Ecologist, USGS, GCMRC

Work Category: High priority research

Objectives

1. *Build a strong conceptual basis for understanding and analyzing linkages between flow management and riparian biodiversity in the Colorado River ecosystem*

2. *Determine the degree to which populations of terrestrial animals respond to spatial and temporal variation in aquatic insect emergence along the Colorado River, with an initial focus on the Glen and upper Marble Canyons.*
3. *Identify whether long-term changes in vegetation have influenced populations of terrestrial consumers, particularly birds and terrestrial insects inGlen Canyon.*
4. *To the extent possible, determine the links between terrestrial fauna and vegetation-flow response guilds.*

Hypotheses/Questions

1. Can we identify and compare quantitative linkages between ongoing vegetation and aquatic and geomorphic monitoring and targeted riparian wildlife assemblages in the Colorado River ecosystem?
2. Can we detect long and/or short-term trends in avian populations by combining historical and newly collected data in an occupancy modeling framework? Are short-term trends for insectivores linked to changes in annual aquatic production?
3. To what degree does swallow and bat activity track spatial and temporal patterns in insect emergence from the Colorado River? Can their activity serve as a continuous noninvasive index of insect emergence?
4. How have terrestrial arthropod communities responded to relatively recent changes in dam operations, including increased frequency of HFEs (which may remove litter within the inundated area); how have communities changed in response to increasing impacts of tamarisk beetle?
5. How are aquatic-terrestrial subsidies structured spatially and do spiders distribute themselves to take advantage of these subsidies? What proportion of spider consumption is based on terrestrial versus aquatic sources?

Rationale/Justification

Riparian environments comprise critical habitat for terrestrial fauna along the Colorado River corridor (Carothers and Brown, 1991; Kearsley and others, 2006; Ralston, 2005), yet the mechanisms that link flow management with riparian biodiversity are poorly understood. A focused effort to expand our knowledge of the pathways linking flow with biodiversity, and their relative strength, is a valuable step forward in our efforts to understand and conserve the Colorado River ecosystem.

Terrestrial fauna of the Colorado River may be affected by flow management from Glen Canyon Dam via two fundamentally different pathways: 1) changes in the availability of *emergent insect* prey from the Colorado River and 2) the density and composition of the *riparian vegetation* that provides habitat for many of these animals. Although the structure of riparian food webs and animal populations has been conceptually sketched (e.g. Suttkus and others, 1976, Spence 2004, Yard and others, 2004, Kearsley and others, 2006), trends in the structure of these food webs, and riparian food web response to changes in aquatic food webs, are poorly known. Moreover, we do not yet know the relative strengths of trophic-driven effects of emergent insects in comparison to the effects of vegetation structure and composition. We will employ the method of multiple working hypotheses to (Chamberlin 1965) to explore the relative strength of the two causal pathways.

Emergent insects—The emergence of adult insects from aquatic ecosystems (i.e., streams, rivers, lakes) represents a key source of energy and nutrients that supports terrestrial food webs and consumers including birds, bats, lizards, toads, frogs, and spiders (Nakano and Murakami 2001, Sabo and Power 2002, Baxter and others, 2005). The availability of adult life stages of aquatic insects as prey can be critical to supporting the stability and biodiversity of riparian food webs (Nakano and Murakami 2001, Sabo and Power 2002, Baxter and others, 2005). The aquatic invertebrate assemblage of the Colorado River in Glen, Marble, and Grand Canyons contains only two common groups: midges and blackflies (Diptera: *Chironomidae* and *Simuliidae*), with midges being particularly abundant (Cross and others, 2013). Research has demonstrated that inter-annual differences in flow management (e.g., spring HFE's, occasional large volume releases associated with equalization) can drive increases in the production of midges and blackflies (Cross and others, 2013, Kennedy unpublished data). It is well established that rainbow trout (Oncorhyncus mykiss) populations, which are studied and monitored closely, have responded strongly to these inter-annual changes in aquatic insect productivity (Cross and others, 2011; Korman and others, 2011; Korman and others, 2012). Previous work in Grand Canyon has demonstrated that emergent insects, particularly midges, are a key prey item for several bird species (Yard and others, 2004). Thus, occasional pulses of aquatic insects associated with infrequent flow events may also lead to increases in the populations of terrestrial animals that also prey on emerging insects (i.e., bats, some bird species, spiders), but this has never been evaluated.

In addition to tracking temporal variation in emergent insects, terrestrial animals may also be tracking spatial variation in emergent insect availability. Within river reaches, terrestrial fauna that rely on aquatic subsidies are expected to be more common at sites near to aquatic production hotspots (e.g., riffles), whereas other factors may affect the amount of insect emergence across reaches. Specifically, citizen science monitoring indicates emergent insect availability is greatest in parts of Lower Marble Canyon (RM 30-50) and the Muav Gorge (RM 140-160), and lowest in Furnace Flat and Upper Granite Gorge (RM 60-90) and Glen Canyon (RM -15 to 0) (Kennedy and others, unpublished data).

Riparian vegetation— Habitat availability likely acts a primary filter determining which terrestrial fauna are found locally. As vegetation communities of the Colorado River riparian zones expand and contract in response to changes in flow management and other perturbations (e.g., *Tamarix* beetle invasion), the density and composition of terrestrial animals will likely respond in kind. Changes in animal populations that are mediated by riparian vegetation will occur over long time scales (i.e., many years to decades), while changes in animal populations that are mediated by emergent insect prey will occur over shorter time scales (i.e., seasonally to annually). Understanding the relative importance of these factors, as well as association between terrestrial fauna and vegetation-flow response guilds will help create a better understanding of how terrestrial fauna will respond to future dam operations.

Choices of study organisms are driven by many factors. Bats and certain bird species (e.g., swallows) can be monitored relatively cheaply using either remote technology or citizen scientists, and rely heavily on aquatic insects emerging from the river (are thus are most likely to respond to spatio-temporal variation in the amount of emergence). Birds and terrestrial arthropods have been well studied in the past, particularly in Glen and Upper Marble Canyons, providing reference conditions to quantify long-term population changes. Within these two groups, we hypothesize that certain species (e.g., yellow warblers and spiders) may be more closely linked to the aquatic ecosystem than other species.

Methods

This project is intended to be implemented in two phases, starting with analysis, synthesis, and conceptual model development in FY 2015 , and followed by targeted research projects that will test the aquatic and terrestrial pathways in FY 2016 and 2017. This project element will summarize and synthesize current understanding of linkages between flow and riparian biodiversity, and utilize information and insights gained from past work. Specifically, it emphasizes the vegetation response-guild work and insect emergence monitoring conducted in FY13–14. It will also include some analysis of historic data, particularly breeding bird data collected in the 1990s in Glen Canyon and studies of terrestrial arthropod communities ~5 years ago. This project will also involve field work to collect new data. Broad tasks for this project follow.

1. Task 1 (FY15): Develop a concept paper summarizing and articulating hypothesized linkages between flow variables and riparian biodiversity in Grand Canyon. Specifically, the paper will evaluate existing data and information about aquatic and terrestrial pathways. This paper will also articulate a riparian research agenda for testing such hypothesized linkages in an adaptive management context, which will guide subsequent fields studies.
2. Task 2 (FY15): Hold a scoping workshop with project principals and other scientists to decide upon the appropriate consumer taxa and field sampling locations for target studies.
3. Task 3 (FY16–17): Work with a graduate student to prepare field study in Glen Canyon todevelop and test methods for quantifying the abundance and distribution of targeted riparian consumers (swallow,bat species, and test whether feeding concentrations are closely linked to patterns of emergence, as we hypothesize. Possible approaches include cost-effective remote automated cameras positioned to capture hourly pictures of swallows and fixed acoustic recorders for quantifying bat activity and species composition. Additionally, we will also develop standardized techniques for quantification of swallow abundance and bat activity that can be used throughout Grand Canyon by citizen scientists.
4. Task 4 (FY16–17: Develop project toinvestigate changes in the abundance and distribution of breeding bird populations in Glen Canyon using sampling methods and fixed locations previously surveyed by John Spence (National Park Service) in the 1990s, and reanalyze both the historic and new data using occupancy methodswith respect to changes in riparian vegetation structure and guild composition using FY13–14 monitoring data, and if feasible, with respect to FY13–14 patterns of aquatic insect emergence.

Outcomes and Products

- Deliverable 1: Manuscript describing hypothesized linkages between flow management and riparian biodiversity in the Colorado River ecosystem. Draft FY15
- Deliverable 2: Workshop report summarizing existing datasets, highest priority consumer taxa to sample, and specific sampling recommendations. FY15
- Deliverable 3: Manuscript describing the relationship between aquatic emergence and consumer abundance in a temporal and spatial context. FY17

- Deliverable 4: Manuscript linking bird occurrence and changes in riparian vegetation structure and composition for a 20-year time period at Glen Canyon National Recreation Area. FY17
- Deliverable 5: Annual list of taxa recorded during the duration of the field projects FY16, FY17

Project Element 11.5. Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds

Daniel Sarr, Research Ecologist, USGS, GCMRC
Barbara Ralston, Supervisory Biologist, USGS, GCMRC

Work Category: Research

Objectives

To convene a science expert review panel composed of natural resource managers and riverine research scientists to examine successes and challenges in non-native vegetation control in the Colorado River and Rio Grande watersheds, and to seek recommendations from that group as to how to plan a scientifically-based riparian management control program applicable to the Colorado River ecosystem in Glen, Marble and Grand Canyons.

Rationale/Justification

Native and nonnative woody riparian vegetation expansion is linked to Glen Canyon Dam operations (Turner and Karpiscak, 1980; Mortenson and others, 2011), but removal of woody vegetation through repeated flooding in association with the Experimental High Flow Protocol may have limited success. To achieve desired future conditions for riparian vegetation as outlined by stakeholder of the GCDAMP (Castle memo, 2012), removal of nonnative species and planting of native vegetation with approaches that incorporate future flow regimes may be required. For example, experimental plant removal and plant actions may focus on tamarisk since tamarisk beetle defoliation has occurred along segments of the Colorado River since 2009 (see Project Element 11.2).

Revegetation efforts are often costly and many times the success is unquantifiable. One reason for a lack of quantifiable success is that the project objectives are too vague (Shafroth and others, 2008). Specific measureable objectives help to define the approach for prioritizing sites and the methodology for vegetation removal regardless of the nonnative or native status of the target species. Additionally, incorporating a review of previous riparian restoration projects within the Southwest (Green River in Canyonlands, the Yampa River in Dinosaur National Park, and the Rio Grande River in Big Bend National Park) can identify approaches that may be most successful in identifying expected outcomes, and in estimating costs for project initiation and subsequent monitoring and maintenance. Element 11.1.5 proposes a science panel review to examine successes and challenges in non-native vegetation control in the Colorado River and Rio Grande watersheds and to seek recommendations from that group as to how to plan a scientifically-based riparian management control program applicable to the Colorado River ecosystem in Glen, Marble and Grand Canyons.

Methods

In FY15, convene a review panel –2-day workshop. Panel participants will include:

- Representatives from National Park Units (GRCA, GCNRA, CANY, DINO, BIBE), the BLM with hands-on experience in nonnative plant control in riparian habitats on regulated rivers
- Riparian ecologists and geomorphologists involved in nonnative species control and environmental flows research.

Use case studies from park units, BLM, or tribal land units to describe results (positive/negative) and recommendations for future planning related to riparian management.

GCMRC organizers will work with presenters prior to the review panel to develop a summary document that can be used to plan science-based management and monitoring for nonnative control for the Colorado River ecosystem.

Questions that will drive the discussion and case study narratives

1. What were nonnative control objectives and what were the methods used for control (poison, mechanical removal, etc)?
2. Which effort resulted in greater or less desirable outcomes? (Was there subsequent extensive weed control that was required and greater manpower needed than anticipated for success).
3. What were the criteria used for each site (logistics only? extent of tamarisk cover?) and were there other considerations that should be included in future site selection?
4. How did hydrologic and geomorphic controls influence or inform site location or approaches for nonnative removal or revegetation?
5. How was success assessed? What monitoring occurred prior to and following removal/restoration actions?
6. What should all resource managers consider prior to and following initiation of riparian management control efforts?

One outcome of this panel would be the decision to proceed with development of a multi-agency planning program (in FY16) wherein BoR, GCNP, and GCMRC would work together to develop a science-based program to plan where vegetation control along the Colorado River ought to occur, the methods to be used in removal, and the methods to be used in monitoring success/or challenges.

Timeline: Work and reporting schedule.

	FY 15	**FY 16**	**FY 17**
1st quarter	Identify Review Panel participants, specific questions for each case study and format for case study document	TBD – Potentially Planning program for experimental vegetation control	
2nd quarter	Convene Review Panel (February)	Status Report	

3rd quarter	Draft Case Study Report		
4th quarter	Final Document		

Outcomes and Products

- A journal article that summarizes Case Studies of Nonnative Riparian Vegetation Control within the Colorado and Rio Grande Watersheds.

D.2. Personnel and Collaborations

Personnel from GCMRC include riparian ecologists, aquatic ecologists and wildlife ecologists. Collaborators include individuals from the National Park Service, other USGS Science Centers, the U.S. Forest Service, Northern Arizona University, and masters students affiliated with Arizona State University and Northern Arizona University.

D.3. Deliverables

See "Outcomes and Products" listed by project element, above.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

Field data sheets entered from 2012 and 2013.
Traits database initiated and being populated
Guilds identified – Draft manuscript completed Fall 2014, to be submitted Jan 2015

E.2. Completed Publications

Ralston, B.E., Starfield, A.M., Black, R.S., and Van Lonkhuyzen, R.A., 2014, State-and-transition prototype model of riparian vegetation downstream of Glen Canyon Dam, Arizona: U.S. Geological Survey Open-File Report 2014-1095, 26 p., http://dx.doi.org/10.3133/ofr20141095.

E.3. Publications in progress

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C. and Cagney, L.E. Colorado River, vegetation, and climate: five decades of spatio-temporal dynamics in the Grand Canyon with regulation – to be submitted this summer.

Vegetation monitoring report 2012-2013 in development –Draft to be completed Summer 2014 – Ralston is lead author.

Riparian vegetation response-guilds downstream of Glen Canyon Dam: a tool for monitoring and evaluating flow needs for vegetation. – Preliminary guilds identified, draft manuscript completed by December 2014. Sarr is lead author.

E.4. Presentations at GCDAMP meetings

Sankey, J.B., and Ralston, B.E. Changes in riparian vegetation in the Colorado River Corridor, 1965-present. Glen Canyon Dam Adaptive Management Working Group Meeting August 2013.

E.5. Presentations at professional meetings

Sankey, J.B., and Ralston, B.E., Colorado River, Vegetation, and Climate: Five Decades of Spatio-Temporal Dynamics in the Grand Canyon in Response to River Regulation. Colorado Plateau Biennial Conference, Flagstaff, AZ, September 2013.

Ralston, B.E., and Sankey, J.B., EP43C-0860. Colorado River, Vegetation, and Climate: Five Decades of Spatio-Temporal Dynamics in the Grand Canyon in Response to River Regulation. American Geophysical Union, Fall Meeting, San Francisco, CA, December 2013.

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G. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$241,800**	**$8,000**	**$5,500**	**$48,900**	**$126,000**	**$6,700**	**$51,200**	**$488,100**
X							11.1	Ground-based vegetation monitoring	Ralston et al.	$84,100	$1,500	$1,000	$48,900	$18,800	$0	$21,700	$176,000
X							11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$41,600	$2,000	$1,500	$0	$99,600	$0	$10,000	$154,700
				X			11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$71,000	$2,000	$1,000	$0	$7,600	$6,700	$11,800	$100,100
				X			11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$16,200	$2,500	$2,000	$0	$0	$0	$3,200	$23,900
					X		11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$28,900	$0	$0	$0	$0	$0	$4,500	$33,400

*2 pay periods of D. Sarr's time will be charged to Project 12 to assist in the workshop facilitation.

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY16							
							11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$244,300**	**$13,500**	**$7,500**	**$65,400**	**$139,500**	**$6,800**	**$74,700**	**$551,700**
X							11.1	Ground-based vegetation monitoring	Ralston et al.	$88,700	$1,000	$1,000	$50,400	$19,100	$0	$30,700	$190,900
X							11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$44,900	$2,000	$2,000	$0	$65,900	$0	$12,400	$127,200
				X			11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$63,500	$2,500	$2,500	$0	$7,700	$6,800	$14,800	$97,800
				X			11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$47,200	$8,000	$2,000	$15,000	$46,800	$0	$16,800	$135,800
					X		11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$0	$0	$0	$0	$0	$0	$0	$0

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
X							11.1	Ground-based vegetation monitoring	Ralston et al.	$96,400	$1,200	$1,000	$52,000	$19,500	$0	$41,800	$211,900
X							11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$46,700	$1,500	$2,000	$0	$67,100	$0	$15,800	$133,100
				X			11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$61,000	$2,600	$2,500	$0	$7,800	$6,900	$18,300	$99,100
				X			11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$43,500	$4,000	$2,500	$8,000	$35,000	$0	$16,900	$109,900
					X		11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$0	$0	$0	$0	$0	$0	$0	$0

Project 12. Changes in the Distribution and Abundance of Culturally-Important Plants in the Colorado River Ecosystem: A Pilot Study to Explore Relationships between Vegetation Change and Traditional Cultural Values

Initial Estimate: FY15: $52,000; FY16: $86,400; FY17: $0

GCDAMP Funding: FY15: $52,000; FY16: $80,400; FY17: $0

A. Investigators

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B. Project Summary

The river corridor landscape in lower Glen Canyon and Grand Canyon National Park has undergone significant change during the past several decades. Some of those changes, especially in terms of vegetation, are the result of river regulation by Glen Canyon Dam. The Glen Canyon Dam Adaptive Management Program supports a $10 million program of research and monitoring to study and document linkages between river regulation and riparian responses; however, few GCDAMP studies have attempted to understand how the changes being documented by GCMRC scientists affect cultural perceptions and values of the diverse stakeholders in the GCDAMP. This project proposes to begin to fill that gap by undertaking a pilot study to evaluate how changes in the riparian assemblage of the river corridor, and specifically in the distribution and abundance of culturally-important plant species, has affected attributes of the landscape that are culturally-important to Native American tribes.

This project will involve holding two workshops with tribal stakeholders, riparian ecologists and social scientist to explore and discuss linkages between changes in plant distributions and abundance and affects to the cultural values associated with plants. We will use these workshops to further refine research questions and directions related to changes in the riparian system that tribal participants would like to explore through future research and monitoring. As part of this project, we will compile and synthesize available data focused initially on a subset of culturally-

important plant species and conduct some exploratory analyses; however, the larger aim of this project is to initiate a dialog on how to evaluate changes in the river corridor landscape that are due wholly or in part to dam operations in terms of the affects that these changes may have on cultural values and human perceptions of the landscape, especially those values that are important to tribal participants in the GCDAMP.

This project is intended to serve the interests of the tribes involved in the GCDAMP, as well as the interests of all GCDAMP stakeholders, in several important respects. At a general level, this project proposes to utilize a combination of western scientific data about vegetation in combination with traditional ecological knowledge (TEK) to interpret landscape changes from tribal perspectives and assess how observed changes to culturally-important plant species affect cultural values associated with the riparian corridor. This information will help to inform DOI managers and GCDAMP stakeholders about how changes in culturally-valued vegetation species of the river corridor's riparian landscape affect cultural resource values of tribal participants in the GCDAMP. More specifically, this project will: 1) integrate Native American values and traditional ecological knowledge in a collaborative GCMRC-sponsored science effort that assesses potential dam effects to culturally-valued plant components of the Colorado River riparian landscape; 2) utilize traditional ecological knowledge to identify plant species of cultural importance to multiple tribes, with a focus on plants that are dependent on and potentially affected by changes in river hydrology; 3) compile and synthesize existing scientific and ethnobotanical information about a subset of culturally-valued plant resources; and 4) utilize a combination of traditional ecological knowledge and western scientific information to further enhance understanding of how dam operations and other potential agents of change affect cultural resource values in the CRe. If, after completing this initial study, tribes decide to incorporate the results of this pilot study into their monitoring programs, this could provide another mechanism for further enhancing knowledge transfer between tribal elders, youth, and non-tribal scientists in the context of tribal monitoring programs. In addition, this project supports the interests of multiple GCDAMP stakeholders who would like to see a variety of approaches, including more holistic and qualitative methods, used to assess the effects of Glen Canyon Dam operations on the riparian landscape and the diverse cultural values of the Colorado River corridor. Furthermore, it is aligned with the new Department of Interior Secretarial directive to use a landscape approach for assessing and mitigating effects of energy-related projects on federal lands (DOI 2013, Secretarial Order No.330).

C. Background

C.1. Scientific Background

Landscapes are dynamic, multidimensional constructs of interest to many disciplines, yet landscape studies are rarely conceived as opportunities for inter-disciplinary collaboration (Tress and others, 2001). The natural components of landscapes, and human perceptions about those components, plus the human tendency to modify landscapes, would seem to offer a natural laboratory for exploring linkages between the biophysical and social sciences. Landscape studies provide a perfect opportunity to create a bridge between the natural and social sciences, because landscapes are, in many respects, culturally and socially constructed concepts (Greider and Garkovich, 1994; Evans and others, 2001) that reflect observed physical and biological attributes filtered through lenses of human perception. For example, the Colorado River corridor in Grand Canyon is often viewed as an example of wild, untrammeled nature by EuroAmerican visitors to Grand Canyon National Park, while this same landscape is viewed by local Native American tribes as a formerly occupied, previously cultivated, and extensively utilized area that was once part of their traditional homelands. These differences in perception reflect significant differences in histories, traditions, and world views, although both groups cherish this landscape, albeit for different reasons and from different points of view.

As attributes of landscapes change, whether through natural processes or as a result of inadvertent or deliberate human intervention, human perceptions about the value and significance of landscapes change as well. We propose to study the linkage between changes in landscape attributes, specifically culturally-important plants, and human perceptions of the landscape, specifically in terms of whether the observed landscape changes constitute positive or negative changes from the perspective of each of the tribes that value the Grand Canyon, in order to explore the relationship between biophysical changes documented through western scientific methods and cultural perceptions of these changes. This information can be used by land and water managers to inform future decisions about how to manage Glen Canyon Dam operations, riparian vegetation, and potentially other vegetation-dependent resources by providing a broader interdisciplinary understanding of how changes in dam operations affect cultural values important to tribal participants in the GCDAMP. This information may also be useful for refining managers' understanding of how to "improve" the condition of riparian vegetation "resources" in keeping with current human societal values.

Although landscapes and their associated vegetation may change for many different reasons, it is well documented that the distribution, density, and diversity of riparian vegetation is directly and indirectly affected by dam regulation of rivers (Williams and Wohlman, 1984; Nilsson and Berggren, 2000; Nilsson and others, 2005). The Colorado River below Glen Canyon Dam is no exception (Stevens and Ayers, 1993; Turner and Karpisak 1980; Webb 1996; Webb, Leake, and Turner, 2007; Sankey and others, in review). Dam-related changes can include shifts in plant densities and in dominant plant communities tied to the frequency and elevation of seasonal inundation, wetting-drying cycles tied to diurnal fluctuations, periodicity and magnitude of flooding, and other types of dam-controlled disturbances. In lower Glen and Grand Canyons, as a result of hydrologic changes due to the presence and operation of Glen Canyon Dam, riparian vegetation has moved downslope and become much denser (Sankey and others, in review), while some of the old high water zone vegetation has died or is senescent (Anderson and Ruffner, 1988; Carothers and Brown, 1991). These changes have resulted in a river corridor landscape that appears significantly different in certain respects from the one that existed prior to the construction of Glen Canyon (Webb, 1996).

Given that cultural values are embedded in landscapes (Stephenson 2005, 2008; Wu 2010), Glen Canyon Dam operations that affect the distribution and abundance of vegetation and associated habitats can also potentially affect the culturally-valued attributes of the landscape. The question that remains to be answered is how and in what respects have cultural resource values associated with the riparian landscape been altered, and how do perceptions of change vary across the different cultures that place value on these resources?

The term "ethnoecology" is often used to describe the study of human perceptions of ecological relationships. As originally conceived, ethnoecology referred explicitly to indigenous perceptions of ecological relationships (Conklin, 1954; Fowler 2000). One early proponent of ethnoecology (Frake 1962) maintained that early efforts to understand a particular cultural group's relationship to its surrounding environment using typical western scientific methods were insufficient because they simply inventoried and categorized plants and animals according to the Linnaean system used by EuroAmerican scientists, which did not capture the unique cultural concepts and complex understanding of the indigenous group's ecological knowledge; instead, Frake (1962) argued that it was essential to "describe the environment as the people themselves construe it according to the categories of their ethnoscience." Thus, the original meaning of the term ethnoecology was in many respects synonymous with the phrase "traditional ecological knowledge" in widespread use today.

Traditional ecological knowledge (TEK) embodies the accumulated wisdom of individual indigenous cultures about ecological relationships based on multiple generations of interacting with and using the products of a local environment. Although several definitions of TEK can be found in the literature (e.g., Lewis 1993; Berkes 1999; Mailhot 1993; Miraglia 1998; Usher 2000), the most commonly cited one is from Berkes (1999): "A cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment." This definition captures the holistic view of ecological knowledge that most indigenous people share in common. Although several scholars have explored the common ground between TEK and western science (e.g., Argawal 1995a, 1995b; Barnhardt and Kawagley, 2005; Berkes and others, 2000; Houde, 2007; Tsuji and Ho 2002), there are some widely recognized differences that make the integration of these two knowledge systems challenging and problematic. These differences reflect fundamental differences in how most western scientists and indigenous people conceptualize the universe and humans' place within in it (Berkes, 1999; Cajete, 2000; Casimiri, 2003; Lertzman, 2010). For example, in contrast to western science, the accumulated ecological wisdom of multiple generations of indigenous users of a particular landscape typically includes each culture's unique understanding of how ecological events and processes interface with and may be influenced by non-biophysical dimensions (e.g., spiritual aspects) of the universe. Thus, TEK can and often does include spiritual and metaphysical aspects that are foreign to most western scientist's perceptions of ecological relationships. This difference presents just one of several challenges to integrating TEK and western science perspectives (Berkes, 1999; Houde, 2007; see also Nadasdy, 1999, 2003).

In recent years, the field of ethnoecology has evolved to incorporate a more holistic and inclusive perspective (Fowler, 2000) in which both western science and indigenous knowledge systems contribute to assessing an array of environmental challenges, changes and effects (e.g., Martin, 1995; Nazarea, 2003). While it might be beneficial for the GCDAMP to undertake a comprehensive ethnoecological study of the river corridor in the future, such an all-encompassing study is not proposed at this time. Instead, for this pilot project we propose to initially focus on documenting changes to a subset of culturally-valued plants and explore through a series of workshops how this information, as well as other information that may be collected in the future, can contribute to furthering understanding of how environmental changes that are due at least in part to operations of Glen Canyon Dam, may affect cultural values important to Native American participants in the GCDAMP. Based on the outcomes of this initial pilot study, we may expand the scope of this work in the future to include other plants and/or other contributing landscape components such as animals.

All of the tribes involved in the GCDAMP possess considerable knowledge of the terrestrial riparian and upland landscapes of the Colorado Plateau from multi-generational use of these resources for daily sustenance, medicines, and ceremonial purposes. For example, ancestors and relatives of the Hualapai and Southern Paiute gathered plants for food, medicine and ceremonies and hunted sheep and other fauna in the western portions of Grand Canyon well into the first decades of the 20th century, while Navajo people used Glen and Marble Canyon for grazing and watering livestock and collecting medicinal plants into the recent historical era (Stoffle and others, 1994; Stoffle and others, 1997; Roberts and others, 1995). These traditional activities require an intimate knowledge of the seasonality and distribution of plants based on centuries of prior experience living within this environment and using plants for various purposes. This knowledge and its application through extensive traditional use of plants as food, medicine, and utilitarian materials contribute to each tribe's perception of their own unique identity (*sensu* Stephenson, 2008). Thus, in contrast to most scientists and stakeholders involved in the GCDAMP, many Native American tribal members view the river corridor landscape as a *cultural* resource, and many of its associated plants are likewise viewed as *cultural* resources, in addition to being valued as habitat for animals.

In contrast to the time depth of Native American traditional knowledge, studies of plants in the Grand Canyon river corridor by western scientists date back less than a century to the late 1930s, when Elzada Clover, a professor of botany from the University of Michigan, and her assistant Lois Jotter, conducted the first botanical inventory in the river corridor of Grand Canyon (Clover and Jotter, 1944). In the late 1950s, additional inventories and studies were undertaken by scientists affiliated with the University of Utah in anticipation of the inundation of the Glen Canyon reservoir (Woodbury and others, 1958, 1959a, 1959b). Starting in the 1970s and continuing through the 1980s, more detailed studies of specific plant distributions and their response to Glen Canyon Dam operations were undertaken by National Park Service scientists and by other scientists who worked for the Bureau of Reclamation's Glen Canyon Environmental Studies (GCES) program (e.g., Anderson and Ruffner, 1988; Carothers and others, 1976; Carothers and Brown, 1991; Stevens, 1989; Stevens and others, 1995; Stevens and Waring, 1986). Beginning in the early 2000s, U.S. Geological Survey scientists working in collaboration with various academic researchers undertook additional vegetation and ecological studies focused on the riparian zone (Kearsley and others, 2006; Ralston, 2005; Ralston and others, 2008). In addition, several USGS-sponsored studies used the replication of historical photographs to document changes to both the riparian and high desert vegetation of the river corridor through time (e.g., Turner and Karpisak, 1980; Webb, 1996, Webb and others, 2007). Other studies focused on evidence from the dendrochronological record to interpret dam-related changes in the distribution and abundance of specific riparian species, such as Goodding willow and netleaf hackberry (Mast and Waring, 1997; Salzer and others, 1996), while still other studies have mapped the distribution of specific species (e.g., Anderson and Ruffner, 1986; Stevens, 2011).

Recently, GCMRC initiated a new study to evaluate effects of Glen Canyon Dam operations on downstream riparian vegetation. This study focuses on monitoring plant-response guilds (see Project 11, this volume). While plant response-guilds monitoring is not specifically focused on tracking changes of individual species, species-specific data is collected with a consistent protocol throughout the length of the Grand Canyon river corridor, and this data could contribute to assessing changes in the distribution and density (percent cover) of culturally-valued plants (see Project 11, this volume).

Other recent work by Amy Draut (2011, 2012) has demonstrated that dam operations can affect vegetation growing well-above the zone of active inundation. These effects occur in part because dam operations influence the distribution of sand bars and other exposed sand areas which serve as sources for wind-blown sand. The distribution of wind-blown sand at higher elevations within the river corridor, and whether it is regularly resupplied or not, influences the texture of surface substrates, water retention capacity of the substrate, distribution of biological soil crusts, and the types, density and distribution of associated plant species. Some of the plants commonly associated with active aeolian landscapes, such as *Sporobolus sp.* and *Oryzopsis hymenoides*, are known to have been highly valued as food sources by many Southwestern tribes. The extent of active and inactive aeolian sand areas has been partially mapped by Draut and others for large segments of the river corridor as part of Project J in the FY13–14 work plan, and will be more completely mapped in FY15–17 as part of Project 4 (this volume), but the extent to which these landscape-scale changes have affected plant species of cultural importance to Native American tribes is currently unknown.

This project intends to build on botanical studies previously undertaken and accomplished by GCES and GCMRC staff and cooperators, as well as recent work initiated by the Hualapai Tribe as part of their pilot TEK study (Hualapai Tribe, 2013). Ultimately, the larger goal of this project is to place species-specific observations of a select group of culturally-valued plants in a larger landscape context and have tribes evaluate these changes from their own unique cultural perspectives as part of their ongoing tribal monitoring programs. The specifics of how this last part will be accomplished will be determined over the course of this project through future collaborative workshops involving tribal partners, social scientists and riparian ecologists.

C.2. DFCs and Key Monitoring and Research Questions Addressed by this project

The recently approved Desired Future Conditions (DFCs) for the Glen Canyon Dam Adaptive Management Program (Ann Castle memo to Secretary Salazar dated April 26, 2012) specify that cultural resources of concern to the program include historic properties that are eligible for listing on the National Register of Historic Places as well as traditionally significant resources such as plants and animals that are not individually eligible for listing on the National Register. According to the DFC document, plant and animal resources as well as landscapes are "[r]esources that have the potential to be considered of traditional cultural significance in the Grand Canyon" although they may not meet the strict definition of significance for listing on the National Register of Historic Places. On the other hand, according to the approved DFCs for cultural resources, Traditional Cultural Properties (TCPs) are potentially Register-eligible cultural resources, and TCPs can include a variety of different kinds of resources, including (but not limited to) "ethnoecological resources" and "the Grand Canyon itself".

According to the DFC document, goals for managing traditional cultural properties include, but are not limited, to the following (only the goals that have relevance to this project are listed):

- Attributes are maintained such as [sic] National Register eligibility is not compromised. These attributes will be specific to the traditionally associated groups and will need to be identified by the federal agencies in consultation with these groups. Attributes may include aspects of the location or physical integrity, as well as intangible elements that link the resource to ongoing traditional practices.
- Culturally appropriate conditions of the resource are maintained based on traditional ecological knowledge; integration of the desired condition is included in relevant monitoring and management programs.

- Maintain ongoing consultation with the groups for whom the resource has traditional value. Because the desired resource of a TCP needs to be determined by the group for whom it has the traditional value, ongoing consultation is necessary to assess the condition of the resource.

The DFC document further species that one metric for cultural resource condition is "impacts at sites that will affect eligibility." Thus, there is a need to document how operations of Glen Canyon Dam potentially affect attributes of TCPs, including ethnoecological resources, and to understand how those changes can negatively (or positively) impact resource integrity. This project will begin to explore linkages between potential dam-related changes to ethnoecological resources within the river corridor and impacts to cultural values that make these resources significant to tribes and potentially eligible for National Register listing.

Over the past decade, GCDAMP stakeholders have identified other core monitoring and research information needs, some of which will be partially addressed through the proposed study. These include the following information needs:

- CMIN 11.2.1 Are the traditionally important resources and locations for each tribe and other groups being affected [by dam operations]?
- RIN 11.2.1 What are the traditionally important resources and locations for each tribe and other groups?
- RIN 11.24 What changes are occurring in cultural resources sites, and what are the causes of those changes?
- RIN 12.9.1 How well does current tribal participation in the AMP research and long-term monitoring programs meet tribal needs and desires?

Finally, in the 2007-2012 Monitoring and Research Plan, scientists and stakeholders identified the following Strategic Science Question which is also relevant to this proposed study:

- SSQ 2-1. Do dam-controlled flows affect (increase or decrease) rates of erosion and vegetation growth at archaeological sites and TCP sites in the CRE, and if so, how?

Research questions specific to this project:

Project 12 is framed around a single broad research question:

- How have culturally-valued vegetation attributes of the riparian landscape of the Colorado River corridor changed since closure of Glen Canyon Dam, and how have those changes (which may be partially or wholly due to dam operations) affected cultural resource values that are important to tribes?

This overarching question has two components, and each requires a different approach:

1. an assessment of biological changes that are relevant to some of the expressed cultural interests of tribes, and
2. an assessment of how those changes may have affected (either positively or negatively) culturally-important aspects of the landscape valued by Native American AMP participants.

D. Proposed Work

This project encompasses two elements with inter-related objectives: 1) an assessment of biological changes that are relevant to some of the expressed cultural interests of Native American AMP tribes, and 2) an assessment of how those changes may have affected (either positively or negatively) culturally-important aspects of the landscape valued by these same groups. Element 12.1 will involve holding two workshops with GCMRC staff and tribal partners, plus other interested stakeholders with particular expertise in riparian and cultural resources, to identity culturally-important plants and other landscape attributes valued by each tribe and to compile and synthesize existing data related to species of interest to multiple tribes. The primary objectives of this first element are three-fold: 1) engage tribes in a collaborative research effort to identify how changes in the riparian ecosystem of the Colorado River corridor has affected or is affecting cultural values and resources that contribute to the identification of Grand Canyon as a Traditional Cultural Property; 2) compile and synthesize data about riparian vegetation and specific species of cultural importance to tribes from a variety of existing sources, including but not limited to previous GCES-era studies, existing GCMRC data, tribal monitoring data, and oblique historical imagery, and 3) analyze these existing data to evaluate the distribution and comparative abundance targeted (culturally-important) plant species in past decades throughout the river corridor landscape as compared with current conditions.

The second component of this project proposes to use the information obtained in Part 12.1 to develop culturally-appropriate methods for eliciting tribal perspectives about the changes that have occurred to the landscape and culturally-important important plant species. Specific methods to be employed in project element 12.2 will be determined collaboratively with tribal participants after they have had a chance to review the results of Part 12.1 and engage in further discussions about possible methodological approaches. Thus, most of the discussion that follows focuses on the methods that will be used to complete Part 12.1.

D.1. Project Elements

Project Element 12.1. Tribal workshops and analysis of cultural landscape change

As stated above, the primary objectives of this first element are three-fold: 1) engage tribes in a collaborative research effort to identify how changes in the riparian ecosystem of the Colorado River corridor has affected or is affecting cultural values and resources that contribute to the identification of Grand Canyon as a Traditional Cultural Property; 2) compile and synthesize data about riparian vegetation and specific species of cultural importance to tribes from a variety of existing data sources, including but not limited to GCMRC's current vegetation program, tribal monitoring programs, and oblique historical imagery, and 3) analyze these existing data to assess how the distribution and comparative abundance particular culturally-important plants may have changed through time.

First Workshop

Early in the first year of the project, as part of project element 12.1, GCMRC will host a workshop to review and discuss the goals of the project, identify plant species of mutual interest to multiple tribes, and to discuss and refine methods for compiling and analyzing available data related to the targeted species that will be the focus of this pilot study. As part of this workshop, GCMRC's riparian ecologist (Sarr) will review data currently being collected for Project 11 and discuss some ways that these data could be analyzed to provide information relevant to tribal interests. In addition, one or more representatives from the Hualapai Tribe will review how historical imagery is currently being applied in their monitoring program to assess vegetation changes from tribal perspectives. The final list of species that will become the focus of subsequent analysis efforts will be determined during the first workshop through consensus of the tribes directly involved in this project. The actual number of species that will become the focus of analysis is currently unknown, but is anticipated to include perhaps 6-8 species, or possibly a few more or less, depending on which species are ultimately selected to be the focus of the pilot study.

Data Compilation and Analysis

With input from the first workshop, GCMRC staff, working in close collaboration with tribal co-leads, will compile existing data from existing sources about the targeted species of interest. Data sources will include, but not be limited to, data from prior GCES-era and GCDAMP-sponsored research, the current and proposed versions of Project 11, tribal monitoring programs, and historical imagery. Based on tribal guidance from the first workshop, we will undertake some initial analyzes of the available data. For example, logistic regression models that are being prepared as part of Project 11 to evaluate linkages between flow variables and riparian plant guilds could be modified to model individual species of cultural significance. Such models present probabilities of occurrence for the taxa studied. This information could be developed and provided to tribes to help target future monitoring efforts. Such models could also be used to identify areas with high habitat suitability for target species but which are not currently occupied by those taxa, thus providing target locations for future restoration efforts.

In addition, we will undertake an analysis of historical imagery; general procedures are described below, but the specific kinds of information to be extracted from the imagery may be refined or modified based on outcomes of discussions during the first workshop:

After the list of target species has been identified, the Project lead working in close collaboration with Project Co-lead Bungart, will undertake a systematic analysis of historical photograph collections to extract information about the distribution and relative abundance of culturally important plants in their predam setting along the Colorado River. Specific collections that will be analyzed include the photographs from the Stanton expedition (1890) and matches of these photographs created by Webb and colleagues in 1990–1991 and 2010–2011 (Webb, 1996; Webb and others, 2011), photographs from the 1871–1872 Powell expedition and the 1923 Birdseye Expedition (some which have been previously matched by Stephens and Shoemaker, 1987 and Barrs and Buchanan, 1994), photo matches documenting vegetation changes by Turner and Karpisak (1980), plus photographs taken by H. Butchart, R. Euler, and D. Schwartz in the early to mid-1960s and by Weeden and others (1975) in the mid-1970s. This analysis will be carried out in conjunction with similar analyses being undertaken for other purposes as part of Project 4.

An effort will be made to identify photographs from a variety of temporal contexts distributed throughout the length of the river corridor over a variety of geomorphic settings. Primary emphasis will be placed on riparian species located immediately adjacent to the historically-active river channel. The intent is to provide a reasonably representative diachronic picture of the river corridor landscape immediately adjacent to the historically-active channel. We estimate that out of approximately 800 historical photographs that will be initially sorted, perhaps 100-150 historical photographs will contain sufficiently detailed images of vegetation to allow species identification; these images will provide the basis for the historical photo analysis component of this project and will serve as the "sampling frame" for characterizing changes in plant distributions throughout the river corridor.

Using analytical methods previously developed by Webb (1996) for comparing the 1890 Stanton photos and 1990 replicates, plus other existing data previously compiled by Webb and others, GCMRC staff will systematically analyze and qualitatively assess changes to specific plants of traditional cultural importance to tribes. In addition to abundance and/or cover of specific plants, other variables may also be assessed. The full range of variables to be analyzed will be determined through discussions with tribal participants during the first workshop. At a minimum, the photographic analysis will identify whether the same plants are present in the same areas today, and whether their abundance appears to have increased or decreased in each photograph using a simple ranked scale (e.g., no apparent increase/decrease, slight increase or decrease (less than 25% difference in individuals or total cover -- the exact metric will depend on the plant species being evaluated), moderate increase or decrease (25–50% difference) or significant change (>50% difference). We will also use the photographs to qualitatively characterize the context in which the plants of interest occur, noting any apparent physical changes to local context associated with observed plant changes (e.g., differences in characteristics of fluvial deposits, biological soil crust cover, aeolian sand cover, associated vegetation, etc.) Specific protocols will be developed in consultation with tribal partners for recording these observations to ensure consistency, comparability, reliability and utility of resulting data. While conducting the photo analysis for Project Element 12.1, photographs taken at or near locations currently monitored by Tribes will be flagged for potential later use in future tribal monitoring programs. To minimize field time and reduce costs, the photographic analysis will initially rely on existing matches of photographs that have been made through previous replication efforts (e.g., Webb, 1996; Webb and others, 2011). A sample of the photographic matches will be later assessed through field checking and comparing previously documented changes with current conditions observed in the field. Any field work conducted for this project will be accomplished in conjunction with river trips planned for other projects, such Projects 3, 4 and 11, tribal monitoring trips, or Grand Canyon Youth trips.

Second Workshop

Once the preliminary analyses and synthesis of existing information has been completed, we will convene a second workshop in FY16 to review the results of this initial work. In addition to reviewing the initial pilot study results, a primary purpose of the second workshop will be to discuss and refine methods for applying these data in future monitoring and/or research projects. During the second workshop, we will explore a variety of methods of applying these data and/or collecting additional information that is needed to more fully capture the affects to landscape attributes valued by the various tribes.

Project Element 12.2. Tribal evaluations of cultural landscape changes

Project element 12.2 proposes to apply information gleaned through element 12.1 to help tribes design and implement culturally-appropriate approaches for eliciting information from tribal members concerning how documented changes in vegetation affect cultural values associated with the riparian landscape. Project element 12.2 would be led by tribal partners and would focus on eliciting tribal input about the changes to the riparian system along the Colorado River. The AMP tribal representatives have requested that precise methods for eliciting tribal perspectives be determined after they have had the opportunity to participate in the workshops and review the outcomes of Part 12.1 Therefore, the methods described below are just two *possibilities* for how tribal perspectives on vegetation change could be elicited in the future:

1. Choice experiments using historical imagery. Comparisons of historical photographs matched with modern photographs provide one potential way to elicit tribal preferences and perceptions about the positive and negative aspects of observed landscape changes. Methods similar to those previously used by Stewart and others (2003) for documenting recreational river runner's preferences for camping beach characteristics could potentially be modified and applied for this purpose .
2. Semi-structured interviews. Another potential approach would be to use comparisons of photographs to elicit tribal members' perspectives through semi-structured interviews. Respondents' preferences could be documented through completing an interview form or perhaps through employing other recording media to document responses. Interview responses could then be compiled and analyzed using previously tested methods such as those described by Toupal (2003).

As described previously, the final choice of methods to be used for eliciting tribal perspectives on landscape and plant-specific changes will be determined through a review of potential methods, followed by focused discussions during the second workshop.

D.2 Personnel and Collaborations

This project will be led by Helen Fairley, GCMRC Social Scientist, in collaboration with multiple tribal cooperators. Peter Bungart will lead the Hualapai Tribe's participation in this project. Bungart is also co-lead of the Hualapai Tribe's ongoing TEK project, and his experience and insights gained from this earlier work, plus his knowledge of managing culturally-sensitive databases, will be essential to conducting this project. Tony Joe, a Supervisory Anthropologist with the Navajo Nation, will help organize and contribute information relevant to the Navajos' perspective on culturally-valued plants and landscapes. Tony will lead the Navajo Nation's participation in elements 1 and 2 of Project 12. Michael Yeatts is an archaeologist with the Hopi Tribe. Yeatts will organize Hopi's participation in Project 12, which will initially focus on element 1. The Hopi's participation in element 2 will depend, in part, on the results obtained from the first year of work. Fairley will have management responsibility for the project, but data compilation and reporting will be carried out collaboratively with Bungart, Joe, and Yeatts and with input from other GCDAMP tribal representatives who choose to participate.

D.3 Linkages to other projects

This project has linkages to other GCMRC projects in the FY15–17 work plan, as well as to at least one project previously sponsored by Reclamation in the FY13–14 work plan.

Project 11 will collect information about current plant species distribution and abundance, which may be useful for documenting changes in the abundance and distribution of culturally-important plants. Daniel Sarr, who is a co-lead on Project 11, will contribute to Project 12 through providing information about the ecology and distribution of riparian plants, and by providing guidance on sampling designs, as appropriate. Charles Yackulic, who is also a member of the Project 11 team, will assist with evaluation of statistical power and other considerations for making sound inferences about the significance of plant changes documented through Project 12.

Some work being conducted as part of Project 4 may benefit the work in Project 12 because both projects will analyze the same sets of historical imagery to identify landscape changes specific to each project. In particular, Project 4 will analyze changes in the amount and locations of active aeolian landscapes throughout the river corridor, and this information may also be relevant to understanding changes in the distribution and abundance of some culturally important plants and landscape characteristics considered by Project 12.

In FY2013-2014, Reclamation funded the Hualapai Tribe to undertake a pilot TEK study. This study will be completed during FY2015. One part of this Hualapai TEK study is exploring the use of historical imagery to document changes in vegetation that is specifically valued by the Hualapai Tribe. It is anticipated that information coming from the Hualapai's pilot TEK study may be useful for informing the historical photo analysis work proposed as part of element 12.1 and may also be useful for guiding how historical imagery can be used by other tribes in future monitoring work.

Finally, depending on which species become the focus of analysis in Project 12, some of the data being compiled and synthesized through Project 12, such as information about the geomorphic setting of specific plants, may prove useful for informing future plant restoration efforts currently being proposed by the Hualapai Tribe in collaboration with Grand Canyon National Park as part of the FY15–17 work plan.

D.4 Deliverables

A USGS report will be prepared at the end of the project documenting the changes that have been compiled and observed through the review and synthesis of existing studies and the intensive photo analysis. This report may also include a summary of observations made by tribal members, to the extent that tribes are willing to share their observations.

A journal article will be collaboratively prepared at the conclusion of the project documenting the work accomplished and its strengths or weaknesses as a model for incorporating tribal perspectives in science programs that can be potentially applied to other adaptive management programs in the future.

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F. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$19,600**	**$5,000**	**$2,000**	**$5,000**	**$15,000**	**$0**	**$5,400**	**$52,000**
X						X	12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$19,600	$5,000	$2,000	$5,000	$15,000	$0	$5,400	$52,000
X						X	12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0
FY16																	
							12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$20,000**	**$2,500**	**$5,500**	**$5,000**	**$45,000**	**$0**	**$8,400**	**$86,400**
X						X	12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$20,000	$2,500	$5,500	$5,000	$15,000	$0	$7,500	$55,500
X						X	12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$30,000	$0	$900	$30,900

Note: In addition to the GCMRC salary listed for FY15 and 16 (above), up to two pay periods of Sarr's time and 1 pay period of Yackulic's time, both of which are currently covered in the Project 11 budget, will be devoted to Project 12 workshop preparation, participation, and data analyses in each fiscal year.

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY17																	
							12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
X						**X**	12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0
X						**X**	12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0

Project 13. Socioeconomic Monitoring and Research

Initial Estimate: FY15: $176,100; FY16: $220,300; FY17: $356,100

GCDAMP Funding: FY15: $176,100; FY16: $204,900; FY17: $338,300

A. Investigators

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B. Project Summary

During the past three decades, socioeconomic monitoring and research in the Glen Canyon Environmental Studies and Glen Canyon Dam Adaptive Management Program (GCDAMP) have been limited (Hamilton and others, 2010). Previous research has indicated that the economic value of recreation and other downstream resources are impacted by Glen Canyon Dam (GCD) operations; however, because these studies were conducted 20 to 30 years ago, the findings are out-of-date, as dam operations and resource conditions have changed since that time (Bishop and others, 1987; Welsh and others, 1995; U.S. Department of Interior, 1996; USGS, 2005).

This project is designed to identify recreation and tribal preferences for, and values of, downstream resources and evaluate how preference and value are influenced by GCD operations. In addition, the research will integrate economic information with data from long-term and ongoing physical and biological monitoring and research studies led by the Grand Canyon Monitoring and Research Center (GCMRC) to develop a decision support system that will improve the ability of the GCDAMP to evaluate and prioritize management actions, monitoring and research (Hamilton and others, 2010).

This project involves three related socioeconomic monitoring and research studies. These studies include: (a) evaluation of the impact of GCD operations on regional economic expenditures and economic values associated with angling in the Glen Canyon National Recreation Area (GCNRA) downstream from GCD, and whitewater floating in Grand Canyon National Park (GCNP) that begins at Lees Ferry (Project Element 13.1); (b) assessment of the impact of GCD operations on tribal preference for and value of downstream resources (Project Element 13.2); and (c) development of decision methods, using economic metrics, to evaluate management actions and prioritize monitoring and research on resources downstream of GCD (Project Element 13.3).

This project will be coordinated with related economic research efforts implemented by the National Park Service (NPS) and U.S. Bureau of Reclamation (Reclamation) in conjunction with the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS). The NPS is conducting research to provide current economic values of ecosystem resources downstream of GCD. In addition, Argonne National Laboratory, contracted through Reclamation, has made significant advancements in the power system analysis modeling for the LTEMP EIS that provide information on the economic value of hydropower production at GCD under different management alternatives. These coordinated efforts to determine individual preferences for and economic values of downstream resources, and the development of decision methods to improve decision making abilities of GCDAMP are necessary to evaluate and prioritize management, monitoring, and research decisions.

C. Background

Recreation

The Grand Canyon Protection Act (GCPA) of 1992 states that, "long-term monitoring of Glen Canyon Dam shall include any necessary research and studies to determine the effect of the Secretary's actions under section 1804(c) on the…recreational…resources of Grand Canyon National Park and Glen Canyon National Recreation Area" (GCPA, sec. 1805(b)). Bishop and others (1987) were the first to establish a relationship between dam operations and recreational preferences and economic values related to angling in GCNRA and whitewater floating in GCNP. Nearly 30 years have passed since this comprehensive study of regional recreational expenditures and preferences for and economic values of releases at GCD. The characteristics of recreational resources have changed significantly since this research was conducted. Specifically, alteration of diurnal flow patterns and greater whitewater floating opportunities resulting from The Operation of Glen Canyon Dam, Record of Decision (ROD) (U.S. Department of Interior, 1996), and the Colorado River Management Plan (NPS, 2006), respectively, have changed the whitewater floating experience. The angling experience has also changed in Glen Canyon since the Bishop and others (1987) study as a result of fluctuations in catch rates and fish condition and modifications to angling regulations (Loomis and others, 2005).

Additional research was conducted in GCNP to assess whitewater floater trip preferences; although the research did not identify specific economic values of flows for whitewater floating trips (Stewart and others, 2000). Furthermore, the economic information related to recreation will not be updated through empirical research for the LTEMP EIS (Harpman, 2013). Because it is important to understand the potential effects of dam operations on the recreational experiences in GCNRA and GCNP, there is a need to update and extend the original Bishop and others (1987) study. Undoubtedly, this research will contribute to a primary GCDAMP goal, which is to "maintain or improve the quality of recreational experiences for users of the Colorado River ecosystem, within the framework of the GCDAMP ecosystem goals" (USGS, 2006).

Native American Tribes

The operation of GCD also has direct and indirect effects on downstream resources of cultural value and traditional use in GCNRA and GCNP. The GCPA of 1992 states that, "…monitoring programs and activities conducted under subsection (a) shall be established and implemented in consultation with…Indian tribes…" (GCPA, sec. 1805(c)). The GCDAMP has also recognized a need to maintain effective consultation with tribes to appropriately incorporate tribal values into the GCDAMP.

> "Because culture defines the roles that resources play in that culture, only members of that culture can assess the status or health of the resources. Therefore, measures for resource status or health and appropriate management will need to be determined individually by the federal agencies in consultation with the traditionally associated peoples (AMWG, 2012a)."

Research concerning tribal preferences for and values of downstream resources, and assessment of the influence of dam operations on these resources, is lacking (Hamilton and others, 2010). This research, in coordination with the tribes, is critical for furthering the understanding of tribal preferences for and socioeconomic impacts associated with resource management decisions within the GCDAMP.

Decision Theory

It is the "absence of decision making mechanisms" in adaptive management (AM) programs that make systematic prioritization of investment in monitoring, research, and management alternatives difficult (Scarlet, 2013). Decision making mechanisms, including the economic assessment of investment in monitoring and research, are important components of AM programs (Doremus, 2010). Recent studies have highlighted the shortcomings of traditional cost-benefit methods when facing the state-dependency and inherent uncertainty in AM programs (Loomis and other, 2009, Bond 2010). Given these shortcomings, optimal control or stochastic dynamic optimization methods have been proposed to evaluate the economics of management actions and monitoring and research efforts (Bond, 2010; Bond and Loomis, 2009; Epanchin-Niell and Hasting, 2010; Springborn and Sanchirico, 2013). These methods use mathematical techniques to identify optimal management actions, including monitoring and research, given an objective (e.g., minimize economic costs) and a set of physical, biological and/or institutional constraints (e.g., humpback cub recovery goals).

Previous research has developed a decision support system for the Colorado River ecosystem (CRE) in GCNRA and GCNP downstream from GCD. Walters and others (2000) developed a decision support system to screen the effect of various management options on downstream resources. While some predictions of resource responses to various management scenarios were accurate, responses to management scenarios of other resources (e.g., sediment storage, native fish) were very uncertain, due to limited empirical data (Walters and others, 2000). More recent analysis in the LTEMP EIS used structured decision analysis to identify alternative future management scenarios, but this process is not comparable to an economically based decision support system (Reclamation, 2014). ***This project element would take the next step in the development of a decision support system to inform the GCDAMP in the organization and evaluation of management actions, monitoring, and research.***

It is pertinent that monitoring and research in the physical science (see FY15–17 Workplan, Projects 1, 2, 3, and 11), biological science (see FY15–17 Workplan, Projects 6, 7, 8, 9, and 10), cultural (see FY15–17 Workplan, Project 4 and 12), and socioeconomic (see FY15–17 Workplan, Project Elements 13.1 and 13.2) programs be integrated into an analytical framework that can inform the GCDAMP in evaluation of future monitoring and research. Developing a decision support system based on analytical methods, such as predictive, integrated dynamic models, is essential when answering questions such as, “how do we quantify and integrate the full range of socio-economic concerns into dam re-regulation, in addition to hydropower concerns (GCDAMP, 2004)?” Therefore, there is a critical need to develop a decision support system within the GCDAMP to assist in the organization, evaluation and prioritization of investment in monitoring and research and improve the economic efficiency of long-run management decisions under uncertainty.

C.1. Scientific Background

The following hypotheses and research questions support the proposed project elements. Given that project elements are a synthesis of monitoring and research, there are components that are not hypothesis driven.

Recreation

Hypothesis 1 (H1) *The operation of GCD influences the economic value of angling in GCNRA, between GCD and Lees Ferry.*

Hypothesis 2 (H2) *The operation of Glen Canyon Dam influences the economic value of whitewater floating in GCNP.*

Hypothesis 3 (H3) *The changes in operation of GCD, since the ROD, have influenced the economic value of angling in GCNRA, between GCD and Lees Ferry.*

Hypothesis 4 (H4) *The changes in operation of GCD, since the ROD, have influenced the economic value of angling in whitewater floating in GCNP.*

Demand for recreation is determined by (a) socioeconomic characteristics (e.g., income, education, age, etc.), (b) quality, (c) substitutes, (d) travel time, (e) crowding, and (f) tastes and preferences (Loomis and Walsh, 1997). Operation of GCD directly impacts the quality of angling in GCNRA and whitewater floating in GCNP (Bishop and others, 1987). For example, different flows affect the ability to operate watercraft during angling and whitewater floating activities and influence trip attributes such as catch rate for anglers and length of time spent on the river for whitewater floaters. Similar to findings by Bishop and others (1987), **H1** and **H2** posit that both anglers’ and whitewater floaters’ economic values increase with increased flows, until an inflection point is reached, at which time economic value decreases with increased flow. Figure 1 is an example of the relationship between an individual whitewater floater’s surplus economic value per trip and average flows.

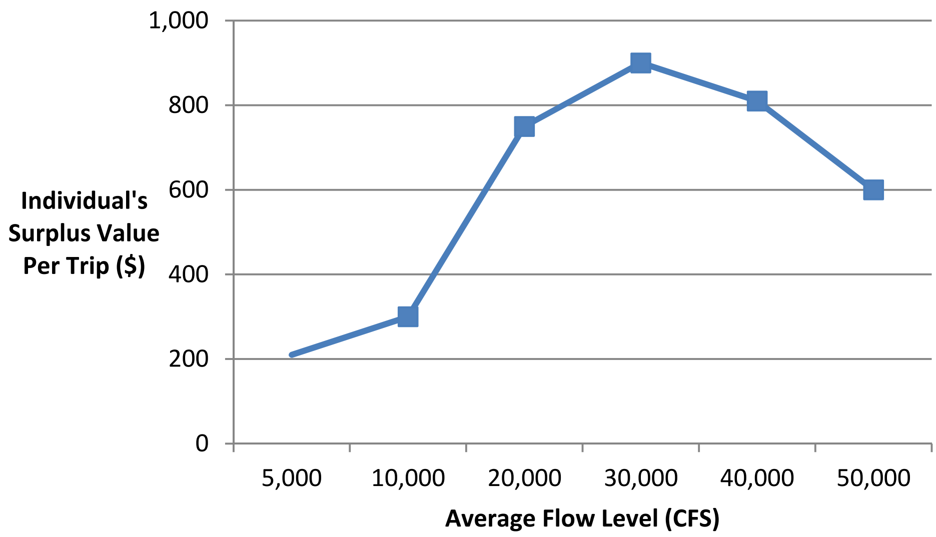

Figure 1. Theoretical Flow Value Curve for an Individual Whitewater Floater (Bishop and others, 1987)

H3 and **H4** posit that both anglers' and whitewater floaters' economic values have increased with the changes in operation of GCD, since the ROD. These hypothesizes are based on the findings of Bishop and others (1987), large fluctuations at moderate flows are not preferred by anglers or whitewater floaters.

While the primary objective of this research is to evaluate the relationship between operation of GCD and economic values of recreational angling and whitewater floating, this project element will also provide information about; (a) regional expenditures, (b) trip attributes of importance, and (c) direct recreational use values (see section D.1). This information is important when conducting short and long-term impact, and other policy related analysis.

Native American Tribes

Hypothesis 3 (H3) *Tribal preferences for and values of downstream resources differ among downstream resource attributes*. To test this hypothesis, the relative ranking, marginal rate of substitution, and parameter estimates of preference relationships among resource attributes (e.g., hydropower, native fish) will be generated and assessed. **H3** posits that there will be significant variation in the preferences for and values of downstream resources by resource attribute. Because tribes may have specific culturally determined "decision processes" and approaches to resource valuation that may limit aggregation of individual preferences, the choice of elicitation methods, and comparison of preferences among tribes (Adamowicz and others, 1998), additional hypotheses to be tested in Project Element 13.2 will be generated following tribal consultation. An additional hypothesis that may be addressed in this project element is:

- Tribal preferences for and values of downstream resources differ among tribes.

This research will enhance understanding of tribal preferences for and values of downstream resources, and perspectives associated with tradeoffs that occur when evaluating management actions and prioritizing monitoring and research decisions within the GCDAMP. This research will develop methods to clearly identify preference for and economic value of resource management decisions, independent of non-economic Tribal cultural values associated with Glen and Grand Canyons.

Decision Theory

This project element will improve the GCDAMP's ability to organize scientific information and evaluate and prioritize, monitoring, research and management alternatives specific to the operation of GCD. For example, in the Non-native Fish Control Downstream from Glen Canyon Dam Environmental Assessment (NNFC) (Reclamation, 2011), it is informally hypothesized that in mitigation of the effects of rainbow trout (*Oncorhynchus mykiss*) on humpback chub (*Gila cypha)* (Reclamation 2011), flow actions may be more cost-effective in the long-run relative to the proposed non-native removal efforts in the Paria-Badger Creek Rapid and Little Colorado River reaches (Reclamation, 2011). This is the type of question this project element will address.

One of the twelve goals of the GCDAMP is to "maintain a high-quality monitoring, research, and adaptive management program" (USGS, 2006). In order to accomplish this goal, it is important to prioritize management actions, including monitoring and research. In fact, several of the eleven other goals of the GCDAMP specify desired resource states and stress actions to achieve these states where "practicable", "feasible", or "within the framework" of other resource goals (e.g., ecosystem goals). This direction calls for a balanced approach to managing resources downstream of GCD. Identifying economic values of downstream resources and establishing a decision support system will assist in the evaluation of actions the GCDAMP recommends and implements through GCMRC to answer research questions specific to its goals.

C.2. Key Monitoring and Research Questions Addressed in this project

This project is organized around hypotheses and research questions (see section C.1) that are based on Strategic Science Questions (SSQs), Core Monitoring Information Needs (CMINs), and Research Information Needs (RINs) previously identified by the GCDAMP. The project also supports the evaluation and prioritization of Desired Future Conditions as identified by the AMWG (2012a.)

Primary SSQ addressed:

- SSQ 2-6. How can tribal values/data/analyses be appropriately incorporated into a science driven adaptive management process in order to evaluate the effects of flow operations and management actions on TCPs?
- SSQ 2-7. Are dam controlled flows affecting TCPs and other tribally-valued resources in the CRE, and, if so, in what respects are they being affected, and are those effects considered positive or negative by the tribes who value these resources?
- SSQ 3-7. How do dam controlled flows affect visitors' recreational experiences, and what is/are the optimal flows for maintaining a high quality recreational experience in the CRE?
- SSQ 3-8. What are the drivers for recreational experiences in the CRE, and how important are flows relative to other drivers in shaping recreational experience outcomes?

Primary Core Monitoring Information Needs addressed:

- CMIN 11.2.1 (SPG revised). Determine the condition of traditionally important resources and locations using tribal perspectives and values.

Research Information Needs addressed:

- RIN 12.1.1 What is the economic value of the recreational use of the CRE downstream from GCD?
- RIN 12.3.2 What are the differences between western science and tribal processes for design of studies and for gathering, analyzing, and interpreting data used in the adaptive management program? How well do research designs and work plans incorporate tribal perspectives and values into the standard western science paradigm? Is it more beneficial to keep the perspective separated?

The development of the proposed project has occurred through communication with and cooperation from the GCDAMP Socioeconomics Ad Hoc Group (SEAHG). The SEAHG has repeatedly identified the proposed project elements as critical information needs (AMWG 2012b). The proposed project elements are also based on coordinated activities with the NPS and Reclamation in conjunction with the LTEMP EIS. The proposed project elements will compliment current economic analysis associated with the LTEMP EIS.

D. Proposed Work

D.1. Project Elements

Project Element 13.1. Economic Values of Recreational Resources along the Colorado River – Grand Canyon Whitewater Floater and Glen Canyon Angler Values – Recommended for Funding (FY15 $69,801; FY16 $ 73,525; FY17 $0)

Lucas Bair, Economist, USGS, GCMRC
John Duffield, Research Professor, Department of Mathematical Sciences, University of Montana
Chris Neher, Researcher, Department of Mathematical Sciences, University of Montana
David Patterson, Professor, Department of Mathematical Sciences, University of Montana

The objective of this project element is to determine preferences, regional expenditures, and economic values of anglers in GCNRA[2] and whitewater floaters in GCNP[3], as affected by operation of GCD, to provide the GCDAMP and federal decision-makers with current recreation resources information for decision making. This project element has been initiated with FY13–14 funds from Project K, Economist and Support ($241,305). Survey printing and mailing costs are included in the FY13-14 Project K funds. The funding request for FY15–16 is only for continued involvement of the GCMRC economist, Lucas Bair.

To accomplish the project objective, a series of economic surveys will be conducted to obtain current information on recreationists' preferences, expenditures, and economic values associated with angler and whitewater floater trips. Specifically, surveys of anglers in GCNRA and whitewater floaters in GCNP will include questions addressing:

- Regional expenditures associated with trip activities such as the cost of transportation, lodging, guide services, and various other local purchases.

[2] For purposes of this project element, anglers in GCNRA include walk-in anglers from Lees Ferry to Badger Creek Rapid.
[3] This project does not include whitewater floaters that begin their trip at Diamond Creek.

- Trip attributes of importance such as crowding, fish catch characteristics, overall trip enjoyment, and other trip qualities.
- Direct recreational use values (i.e., net economic benefits) to the recreationist, as measured by willingness to pay over and above trip costs.
- Variation in direct recreational use values related to a range of flow levels presented in the surveys.

As was the case with the original Bishop and others (1987) study, the proposed project will use a mail survey contact method with a follow-up protocol for non-responders. The respondents will be sent a mail survey packet, followed by a postcard reminder, and, later, by a second survey packet for non-responders. Non-respondents to the second survey packet will be contacted to complete non-response questions.

A random sample from the most recent year's whitewater floaters will be obtained with the assistance of GCNP and outfitters. GCNP maintains a comprehensive mailing list of all members of private whitewater floater parties. Additionally, commercial outfitters maintain mailing lists of the commercial clients. The survey will include: 1) private party floaters, 2) commercial motor powered floaters, and 3) commercial oar powered floaters. The target sample size will be 2,850 whitewater floaters divided equally between private and commercial trip participants. The commercial sample will be further divided equally between oar and motor-powered trips.

Anglers in Glen Canyon, using Lees Ferry downstream to Badger Creek Rapid as access points, will be contacted, in cooperation with Arizona Department of Game and Fish, during high use periods, spring (April-May) and fall (October-November), to participate in the surveys. No *a priori* attempt will be made to stratify the sampling based on guided or non-guided status. However, preferences, expenditures, and economic values of guided and non-guided anglers will be compared within the data analysis. Anglers contacted at Lees Ferry will be asked questions regarding demographics and attributes of their trip. In addition, anglers will be asked to provide contact information. The target sample size is 750 anglers.

Statistical models appropriate for the experimental design and elicitation format of the surveys will be developed to evaluate the relationship between preferences, economic value and trip attributes (e.g., flow levels). The models will provide information on the relative preferences and economic value for trip attributes and the marginal rates of substitution between trip attributes. This information is necessary for the GCDAMP to make informed decisions about the economic tradeoffs that occur, with regard to recreation, when evaluating future management actions (see FY15–17 Workplan, Project Element 13.3).

Project Element 13.2. Tribal Perspectives for and Values of Resources Downstream of Glen Canyon Dam – Funding Uncertain (FY15 $0; FY16 $136,580; FY17 $128,065)

Lucas Bair, Economist, USGS, GCMRC
John Duffield, Research Professor, Department of Mathematical Sciences, University of Montana
Chris Neher, Researcher, Department of Mathematical Sciences, University of Montana
David Patterson, Professor, Department of Mathematical Sciences, University of Montana

The objective of this project element is to identify tribal preferences and values associated with management of resources downstream of GCD in order to inform decision making processes in the GCDAMP. Defining individual tribe's preferred actions or constraints associated with management of downstream resources is important when evaluating potential actions and associated trade-offs. Emphasis will be placed on resources of tribal significance that are directly or indirectly affected by dam operations, experiments, and ongoing management. The assessment of tribal preferences and values will be achieved through focus group meetings with individual tribes, where choice experiment methods will be conducted to explicitly evaluate resource attributes tradeoffs that occur from management of GCD. The project will be implemented in in FY16, with continued dialogue and informational presentations provided by GCMRC staff throughout FY15 to facilitate the proposed research.

The individual project elements will consist of four major tasks:

1. Cooperate with GCDAMP Tribal representatives and Tribal members to review previous studies and tribal programs relating to tribal preferences for and values of resources downstream of GCD and obtain necessary permits to conduct research on tribal land.
2. Conduct initial meetings with individual tribes to obtain permission and gauge interest in participation, identify focus group participants, and develop and pretest focus group survey content to ensure culturally appropriate methodology.
3. Conduct focus group meetings with individual Tribal members to explore preferences for and values of downstream resources.[4] The meetings will use choice experiment methods (Breffle and Rowe, 2002; Harpman, 2008), which are commonly applied in marketing and resource economics studies, to identify these preferences and values. When appropriate, nominal compensation will be provided to Tribal members for their participation in focus groups. Focus groups provide an open forum for clarifying survey methods and participant questions. However, in-person, mail or alternative survey methods will be used if individual tribes discourage the use of focus groups.
4. Analyze survey results and prepare manuscript for publication. Reports and presentations specific to the research methods and results of Project 13.2 will be provided to individual Tribes as requested.

For the choice experiment methods, downstream resource attributes of tribal importance (e.g., hydropower, humpback chub) and their potential variation with different future management actions will be defined in Task 2 and will shape the experimental design. The experimental design will be based on the number of possible scenarios to choose from, where respondents may be asked to evaluate all possible scenarios or just a subset of randomly chosen scenarios if the number of choices are unwieldy. Based on input during tribal consultation, future attribute levels will be either ranked, rated, or evaluated in a choice-based format (two alternative future scenarios compared and one is selected). It is important to note that comparisons among resource attributes can contain explicit cost information (e.g., forgone hydropower revenue) when comparing future resource attributes, or may just compare resource attributes alone. Statistical models appropriate for the experimental design and elicitation format will be developed to evaluate the relationship between preferences, or values, and resource attributes. ***The models will provide information on the relative preferences and values for resource***

[4] Focus groups are considered "qualitative" research and require less time-intensive review by the Office of Management and Budget.

attributes and the rates of substitution between resource attribute tradeoffs.[5] Information gained through this research is necessary for evaluation of management decisions and development of applied decision methods that accommodate tribal preferences for and values of downstream resources (see FY15–17 Workplan, Project Element 13.3). The anonymity of individual focus group participants and scientific integrity of the research is concomitant with the Office of Management and Budget survey review as part of the Paperwork Reduction Act and peer review, respectively.

Project Element 13.3. Applied Decision Methods for the Glen Canyon Adaptive Management Program – Recommended for Funding (FY15 $106,803; FY16 $147,640; FY17 $228,984)

Lucas Bair, Economist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Michael Springborn, Assistant Professor, University of California at Davis
Craig Bond, Economist, Pardee RAND Graduate School

The objective of this project element is to improve the GCDAMP's ability to consider, organize and prioritize monitoring, research, and long-term management alternatives related to the operation of GCD. A decision support system comprised of analytical models, that incorporate economic parameters, will provide prompt assessment capabilities in science and management program planning.

To accomplish this, existing published approaches to resource management under uncertainty will be evaluated. Specific attention will be paid to methods that improve decision making processes when evaluating resource tradeoffs related to monitoring, research, and management decisions. Evaluation efforts will focus on decision frameworks and analytical tools that best apply to the GCDAMP when considering the need for collaboration, complex biophysical/socioeconomic interactions, and constraints on GCDAMP resources.

There are multiple analytical approaches used in decision frameworks that address resource management under uncertainty. These include maximizing expected utility, applying the precautionary principle and other robust decision making processes such as dynamic stochastic programming, optimal control, or simulation methods (Lempert and Collins, 2007). The various approaches differ in the types of scientific information utilized and the way in which decision process outcomes are framed and communicated (Lempert and Collins, 2007).

There are also various types of decision support system frameworks that are important to consider when interdisciplinary teams of scientists and stakeholder groups that hold divergent views, or core values, are involved in the decision process. It is as important to address the decision process, or context, as it is to develop the scientific foundation, or content, of the analytical methods (Norton, 2005; Clifford and Sagoff, 2009).

This project element will develop and implement a decision support system specific to the GCDAMP in a series of model development tasks. Analytical model development of downstream resources will be prioritized for resources that:

1. Contain significant economic value and/or that garner a significant portion of the GCMRC annual budget;
2. Are impacted by operational decisions at GCD; and

[5] Model results will not quantify the economic value of the resource attribute. However, if price based attributes (e.g. hydropower costs) are assessed in the surveys, economic values can be ascertained.

3. Have sufficient predictive modeling frameworks developed to assess future resource states.

The initial focus of this project element will be the development of a bioeconomic model to identify the economically preferred management strategy for established nonnative fish, in relation to humpback chub survival.[6] This is a question explicitly identified in the NNFC (Reclamation, 2011). This task follows the model prioritization structure, (1) ecosystem values (including humpback chub) exhibit significant economic value (Welsh and other, 1995); (2) dam operation impacts non-native fish populations (see FY15-17 Workplan, Project 9), and (3) recent advancements in predictive models of rainbow trout and humpback chub survival have led to opportunities to evaluate humpback chub population management from an economic perspective (Yackulic and others, 2014). This task will evaluate economic outcomes, as part of the Yackulic and others (2014) model, to minimize the cost of rainbow trout removal over time, under different future scenarios. While the exact methodological approach will be determined through model development, the likely approaches include optimization (stochastic dynamic programming or optimal control) and/or simulation based approaches (Epanchin-Niell and Hasting, 2010). Incorporating future scenarios allows for modeling humpback chub recovery goals in various conditions while identifying strategies that are both cost-effective and robust to uncertain future conditions (e.g., climate). This analytical model, and accompanying documentation, will be completed in FY15.

This proposed bioeconomic model utilizes cost-effectiveness analysis. Like cost-benefit analysis, cost-effectiveness analysis is a standard economic practice. However, cost-effectiveness fundamentally asks a different question than cost-benefit analysis. Cost-benefit analysis assigns an overall net benefit (or net cost) to a future management action. Cost-effectiveness analysis in-turn identifies the least cost alternative, when faced with competing or complimentary management actions, to reach a defined objective. In this case, the objective is humpback cub recovery, as defined by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service, 2002). Implementing cost-effectiveness analysis is consistent with the ROD's goal, not to maximize benefits but to determine an operation at GCD that limits impact to hydropower while meeting recovery and long-term sustainability of downstream resources (Reclamation, 1996).

There are several other implications when using cost-effectiveness analysis that are important to recognize. For example, it must be determined that the defined goal is worth achieving. This is demonstrated by either verifying the economic benefit of the objective outweighs the costs associated with achieving the objective or the objective is mandated through a public process. In the case of the humpback chub recovery goals, both the economic value of recovery exceeds the cost of proposed recovery actions and recovery goals are mandated through public process (Welsh and others, 1995; U.S. Fish and Wildlife Service, 2002). Conducting cost-effectiveness analysis also implies that the defined goal will be reached across all possible alternative future scenarios. Again, this is a reasonable assumption based on the recovery mandate (U.S. Fish and Wildlife Service, 2002). This implication is important because it essentially removes the onerous, or in some cases contentious, identification of economic value of downstream resources. The focus is shifted from establishing the benefit of the objective to identifying the most cost-effective way to meet the objective (Sagoff, 2009). This is an important distinction when stakeholders may fundamentally reject attempts to economically value aspect of ecosystem

[6] Management strategies would consider constraints with respect to tribal concerns and other factors (e.g., whirling disease).

resources. Cost-effectiveness analysis isn't appropriate in every context. However, it lends itself to the GCDAMP's task of evaluating and prioritizing management actions, monitoring and research where incremental decisions must be made, under uncertainty, understanding that many overarching objectives are set through public processes.

While the initial task is focused on research to identify the most cost-effective management actions with respect to non-native fish management policies, as identified in the NNFC (Reclamation, 2011), the modeling effort will be expanded in FY16–17 to include other downstream resources that impact rainbow trout and humpback chub populations, better facilitating decision making in the GCDAMP. Specifically, in FY16–17, subsequent tasks in model development will include:

1. Identify the importance of parameter uncertainty on the sensitivity of cost-effective outcomes in the bioeconomic model. Evaluating parameter uncertainty will aid in the identification of the value and prioritization of monitoring and research (i.e., how scientific discovery and monitoring, and reducing model parameter uncertainty, decreases expected management costs) and demonstration of how modeling can prioritize future monitoring and research. This advancement in the analytical model, and accompanying documentation, will be completed in FY16–17.
2. Incorporate additional management variables and associated costs, such as trout management flows at GCD, to improve humpback chub survival, again identifying the most cost-effective management alternatives under different future scenarios. This advancement in the analytical model, and accompanying documentation, will be completed in FY16–17.

The decision support system will be developed over FY15–17 in cooperation with stakeholders, according to stakeholder's expressed needs and the advancement of scientific knowledge at GCMRC. For example, updating the economic value of whitewater floating in GCNP will provide insight into modeling the tradeoffs between flow regimes and recreational experiences (see FY15–17 Workplan, Project Element 13.1). This deliberate process of building a decision support system through the development of individual analytical, predictive models will enable analysts to identify monitoring and scientific information needs and screen policy options as the GCDAMP advances its goals. This process is essential in enabling the GCDAMP to better organize and evaluate the scientific monitoring and research that is provided by GCMRC.

D.2 Personnel and Collaborations

The project lead is Lucas Bair. Collaborators for Project Elements 13.1 and 13.2. include John Duffield and Chris Neher, economists at the University of Montana, and David Patterson, a statistician at the University of Montana. These collaborators will assist with the development and implementation and analysis of recreational and tribal surveys. Collaborators for Project Element 13.3. will include Charles Yackulic and other biology and physical-sciences program staff at the GCMRC, mostly in supporting roles, Michael Springborn, an economist specializing in adaptive management, at the University of California at Davis, and Craig Bond, an economist specializing in adaptive management, at the RAND Corporation. These collaborators will assist with development of applied decision methods.

D.3. Deliverables

Products from this project, led by Lucas Bair, will include annual reports to the GCDAMP, presentations at TWG and AMWG meetings when appropriate, presentations at scientific meetings, and peer-reviewed scientific journal articles. Reports and presentations specific to the research methods and results of Project 13.2 will be provided to individual Tribes as requested.

- In FY16–17, one or two manuscripts will be prepared from the results of Project Element 13.1 for submission to peer-reviewed scientific journals.
- In FY17, one manuscript will be prepared from the results of Project Element 13.2 for submission to a peer-reviewed scientific journal.
- In FY15–17, two or three manuscripts will be prepared from the results of Project Element 13.3 for submission to peer-reviewed scientific journals.

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F. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY15							
							13	**Socio-economic Monitoring and Research**		**$118,800**	**$12,500**	**$1,000**	**$0**	**$22,500**	**$0**	**$21,300**	**$176,100**
				X			13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$54,700	$5,000	$500	$0	$0	$0	$9,400	$69,600
				X			13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$0	$0	$0	$0	$0	$0	$0
			X				13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$64,100	$7,500	$500	$0	$22,500	$0	$11,900	$106,500
										FY16							
							13	**Socio-economic Monitoring and Research**		**$124,900**	**$12,500**	**$11,100**	**$0**	**$171,500**	**$0**	**$36,900**	**$356,900**
				X			13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$57,500	$2,500	$300	$0	$0	$0	$12,900	$73,200
				X			13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$2,500	$10,300	$0	$117,500	$0	$6,300	$136,600
			X				13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$67,400	$7,500	$500	$0	$54,000	$0	$17,700	$147,100

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY17							
							13	**Socio-economic Monitoring and Research**		**$127,400**	**$12,500**	**$1,000**	**$0**	**$171,500**	**$0**	**$43,700**	**$356,100**
				X			13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$0	$0	$0	$0	$0	$0	$0	$0
				X			13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$5,000	$500	$0	$117,500	$0	$5,000	$128,000
			X				13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$127,400	$7,500	$500	$0	$54,000	$0	$38,700	$228,100

Project 14. Geographic Information Systems (GIS) Services and Support

Initial Estimate: FY15: $222,800; FY16: $236,500; FY17: $253,900

GCDAMP Funding: FY15: $222,800; FY16: $219,900; FY17: $241,200

A. Investigators

Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Timothy Andrews, IT Specialist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
TBD, Geographer (GS-09), U.S. Geological Survey, Grand Canyon Monitoring and Research Center

B. Project Summary

Geographic Information Systems (GIS) continues to play a critical role in nearly all of GCMRC's science efforts and is prevalent in many of the projects proposed in the FY2015-17 Triennial Work Plan. It is used across disciplines and is itself a powerful tool for integrating geospatial data collected by many different projects. The GIS Services and Support project is the epicenter of GCMRC's geospatial knowledge and support for a broad range of activities. It supports acquisition of remote sensing overflight data and river-based data collection efforts, provides geospatial expertise across all resources of interest, maintains and preserves all geospatial data holdings, and produces a wide range of cartographic, geographic and analytical output in support of GCMRC's science projects. Linkages to other projects in this work plan are addressed in the Geospatial Data Analysis element of this project (14.1.1.) and more specifically outlined in Table 1 at the end of this project description. This project provides a high-level of support to other GCMRC projects in the form geospatial data processing and analysis, geospatial data management, and the development of web-based services and applications that provide access to GCMRC's geospatial data holdings.

As we move into a new planning cycle, an opportunity exists to promote a vision of how a GIS project will successfully function within GCMRC and meet the current and future needs of scientists, managers and the public alike. Most work performed within this project falls within one of three main tenets: Geospatial Data Analysis, Geospatial Data Management, and Access to Geospatial Data Holdings. These concepts are not new, and have been a part of GCMRC work in various forms over the last 15 years or more. This project description affords us a chance to more clearly define each of these elements and how they relate to individual projects as well as GCMRC's overall mission.

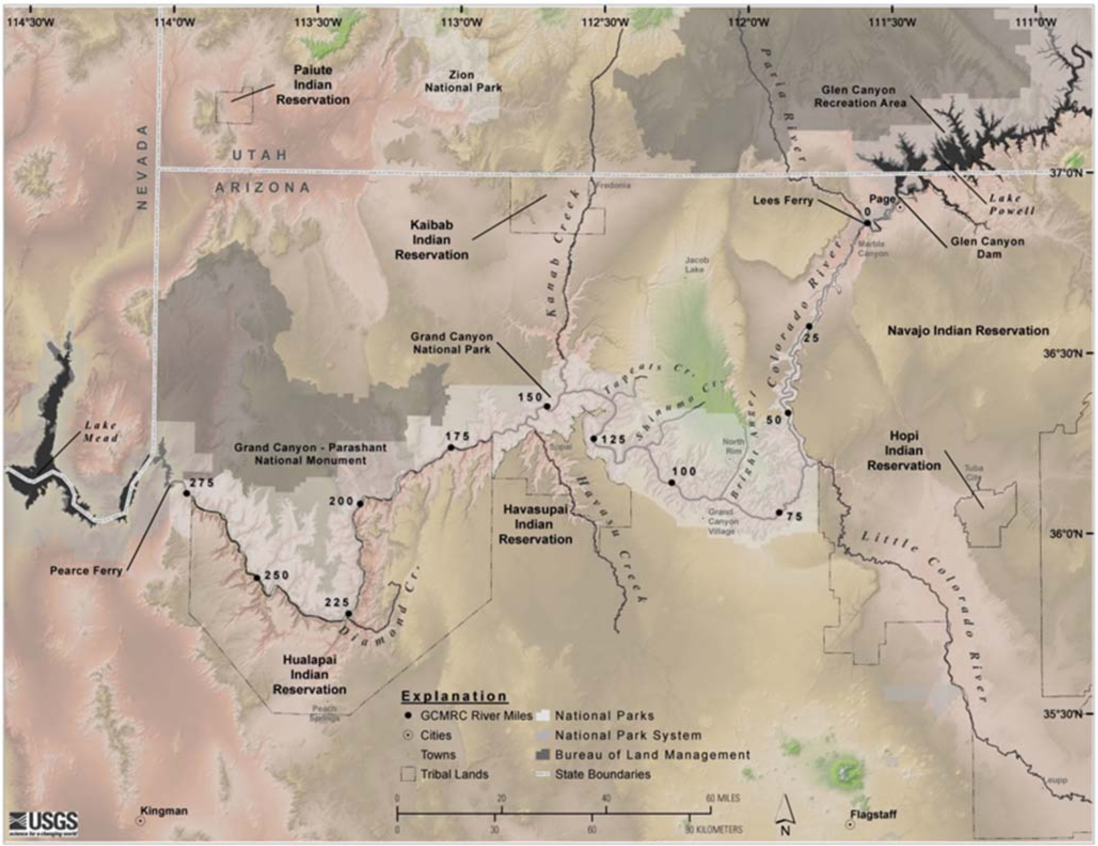

Figure 1. One example of many Grand Canyon location maps designed and produced by GIS staff in support of GCDAMP activities.

C. Background

C.1. Scientific Background

Research and monitoring efforts at GCMRC have led to the collection of a wealth of geospatial information over the last twenty years. Many of GCMRC's geospatial data holdings have large spatial extents (from Lake Powell to Lake Mead), fine resolutions (20-cm pixels for imagery, 0.01 meter spatial tolerances), and large file sizes with tens of thousands to millions of records per file. This presents a challenge to map a considerably large area at very fine scales, as does the sinuosity of the Colorado River and the extreme elevation changes found in Grand Canyon. Challenges also arise in handling, analyzing, storing and serving these unique data sets. The GIS staff at GCMRC has met these challenges by continuing to provide a stable and consistent platform for conducting geospatial processing, analysis and output for over a decade.

The last ten years have seen many advances in the geospatial industry, with some of the more noticeable changes coming in the role that GIS and geospatial data now play in our daily lives. Similarly, the role of GIS within GCMRC has changed during this same time period. The most recent versions of GIS software have become easier to use with more standardized workflows for creating, maintaining, processing and analyzing geospatial data. This has allowed science staff to begin using GIS tools on their own, thus broadening the Center's base knowledge in GIS. It has also increased the amount and level of support requested of GIS professional staff within GCMRC.

Over the last decade, the use of GIS within GCMRC has evolved into a fully functioning, mature, enterprise-level system. All geospatial information collected and produced by GCMRC can be overlaid, analyzed and integrated. More recently, the GIS staff has made a concerted effort to stay at the forefront of technological advances in providing access to geospatial information online. Final versions of geospatial data are available internally through both file-based and server-based platforms, and externally through custom-built web mapping applications on GCMRC's website, as well as other online avenues (see Project Elements 14.3.1 and 14.3.2). Anyone can now access many of GCMRC's most important geospatial data sets online including canyon-wide, aerial imagery (Fig. 2) and elevation data of the CRe between Lakes Powell and Mead, locations of river campsites used by recreationalists, long-term sandbar monitoring DEM surfaces, site photographs of campsites and sandbars, and sandbar deposition photographs before and after recent high flow events. These data serve as a tremendous resource to managers, stakeholders, and members of the general public interested in Grand Canyon and its resources.

The advances made by GCMRC in online mapping applications have already proven useful in supporting management activities such as the development of the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement. In addition, they provide opportunities for scientific collaborations not previously possible.

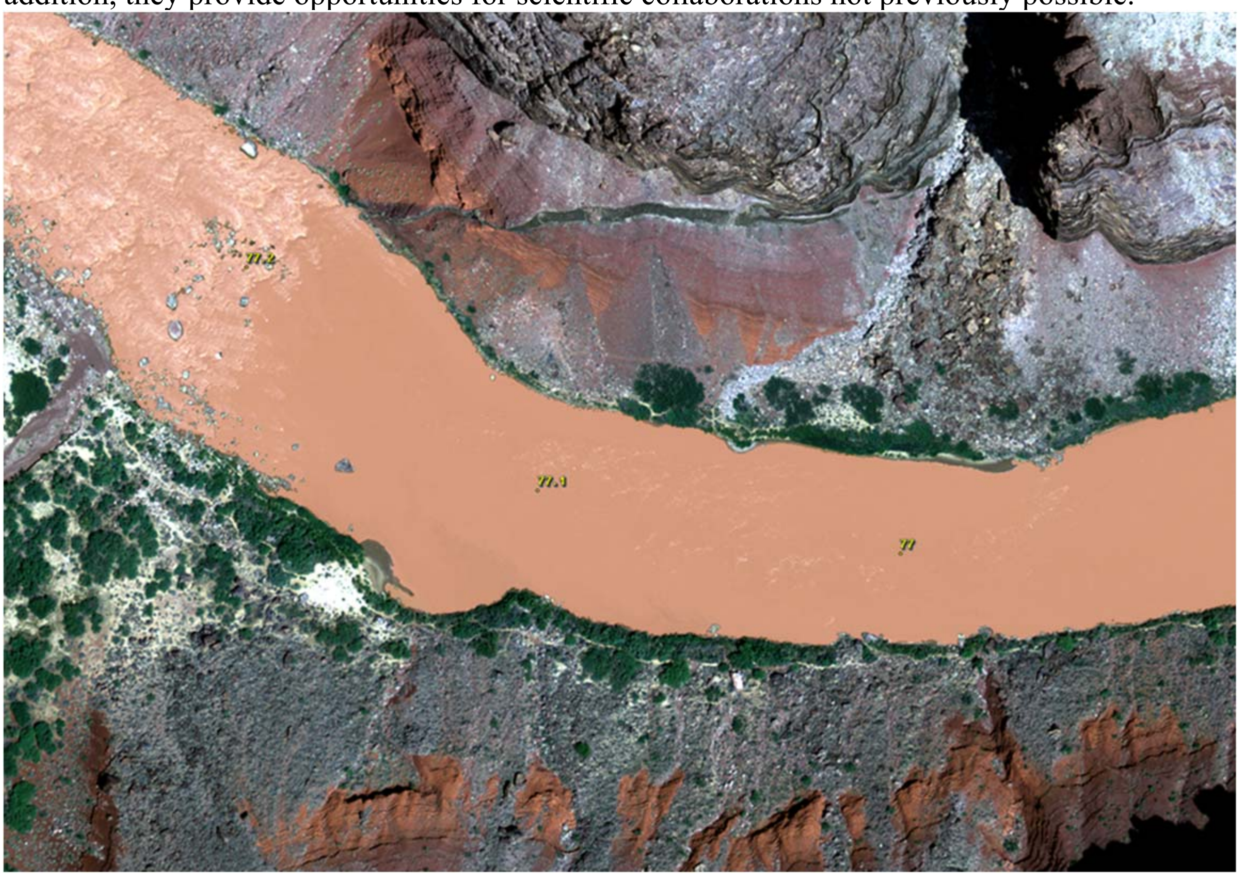

Figure 2. Aerial imagery collected in May 2009 showing the top of Hance Rapid. Digital imagery collected in years 2002, 2005, and 2009, along with many other geospatial data sets, can be viewed online at http://www.gcmrc.gov/

C.2. Management Background

As the science provider for the Glen Canyon Adaptive Management Program (GCDAMP), GCMRC is responsible for providing complete and spatially accurate geospatial data in support of funded GCDAMP projects. Historically, this responsibility was outlined in the Adaptive Management Work Group's (AMWG) original list of program goals (Goal 12: Maintain a high quality monitoring, research and adaptive management program), and upheld by GCMRC's GIS and Survey staff, both formerly a part of a now nonexistent Information Technology (IT) program. The elements of GIS and Survey (Project 3.5) still remain and have continued to provide the expertise required to maintain federal guidelines and standards for data quality and accuracy as well as fully support the needs of GCMRC scientists and managers.

The ability to maintain consistent and accurate geospatial information, perform necessary analyses on geospatial data, and integrate information across projects has been essential to other GCMRC projects directly supporting many of the other GCDAMP goals. Successive refinements of GCDAMP goals, objectives, and questions (Core Monitoring Information Needs, Research Information Needs, Strategic Science Questions, Desired Future Conditions, and the HFE EA) all still rely on GCMRC's ability to maintain, process and serve highly accurate geospatial information, and in some cases, have prompted the need for new or additional data to be collected and processed.

Beginning in 1999, GCMRC's GIS staff undertook the development of a canyon-wide, spatially consistent Geographic Information Systems platform. The centerpiece of this platform was the GCMRC centerline and river mileage reference system that was completed in 2002. This data set cross-referenced the most commonly used river mile systems in existence at the time, and has since become the backbone of all georeferenced information collected or developed along the Colorado River corridor. Nearly all scientific research, published literature, management decisions, and even commercially available river guide books now use this system for referencing locations along the river. The GCMRC centerline and river mileage reference system, as well as all other geospatial data collected or derived within the Colorado River corridor, are dependent on the survey control network (Project Element 3.5). These two components (GIS and Survey) remain closely tied and together have produced a spatially accurate and logically consistent georeference system used by all GCMRC projects. This geospatial system is comprised of data sets, databases, workflows, processing techniques and metadata documentation that is adaptable to new advances in technology, and yet continues to be a stable platform for conducting long-term scientific studies of the Colorado River. Even as management needs change and become further refined, it is anticipated that the role of GIS as both a scientific and management support tool will continue to become increasingly important.

C.3. Key Monitoring and Research Questions Addressed in this project

For relationships between the GIS Services and Support project and key monitoring and research questions, please refer to project linkages briefly described below in Geospatial Data Analysis (14.1.1.) and more specifically listed in Table 1 of this project description.

D. Proposed Work

D.1. Project Elements

Project Element 14.1. Geospatial Data Analysis

Thomas M. Gushue, GIS Coordinator, USGS, GCMRC
Timothy Andrews, IT Specialist, USGS, GCMRC
TBD, Geographer (GS-09), USG, GCMRC

To measure the amount of GIS support provided to all projects in the FY2015-17 Work plan, we estimated the number of pay periods required of GIS professional staff to assist with geospatial related tasks for each project element. The level of involvement was determined in consultation with principal investigators and other researchers for each project with specific geospatial processing, analytical tasks and associated writing assignments described within the appropriate project element. In some cases, senior GIS staff members are assigned as co-investigators to specific projects or project elements that require high-level geospatial application and analytical support (see Project Elements 3.1.2, 3.1.4, 9.9, and 10.1). Proposed research efforts defined in the work plan that will require a significant amount of high-level GIS support include elements of projects 3, 4, 5, 6, 7, 9 and 10. For project elements requiring geospatial support that is lower-level in nature (Projects 8 and 11), the work to be performed is considered to be fairly simple, commonly performed tasks requiring less than one day of one person's time. A listing of GIS support planned for all pertinent project elements is provided in Table 1 at the end of this project description.

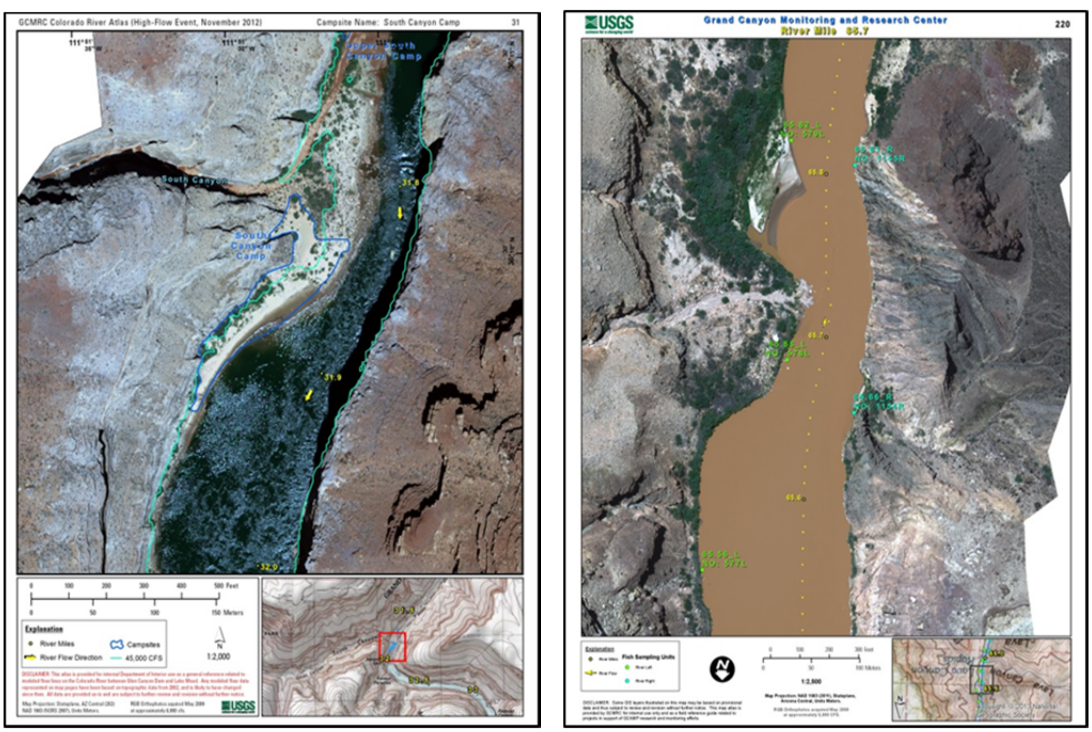

Figure 3. Two examples of map products designed and produced by GIS staff in support of a) GCDAMP management actions, a map series illustrating anticipated inundation areas related to the November 2012 HFE (left), and b) GCMRC

science efforts, a map book series created specifically for the system-wide electrofishing project (right), Project element 6.4 in FY2015-17 work plan.

Project Element 14.2.1. Geospatial Data Management

Thomas M. Gushue, GIS Coordinator, USGS, GCMRC
Timothy Andrews, IT Specialist, USGS, GCMRC
TBD, Geographer (GS-09), USG, GCMRC

Geospatial data and how these data are handled has changed considerably in the last ten years. Improvements in remote sensing technologies have resulted in much larger, more accurate geospatial data sets that require advanced storage and retrieval systems. As a solution, the GIS industry has moved away from the traditional desktop environment (localized software and data) to an enterprise environment consisting of server and client roles where the ability to share large amounts of geospatial data and associated analytical tools is increasingly more important. Previously, individuals processing and maintaining their own individual data sets (i.e. Arc/Info coverages, shapefiles) was the norm; now organizations build GIS services and applications for GIS users to consume in many different ways. The move towards an enterprise GIS system at GCMRC began over a decade ago, however, this effort has gained momentum over the last five years. In 2011, a stand-alone Oracle database was designed and built specifically for storing and serving large amounts of geospatial data. Prior to this time, all tabular and spatial were stored on the same Oracle database server which caused many data storage and access issues. Since 2012, we have been populating an Oracle Spatial Database with a range of geospatial data sets that are used locally by GCMRC for mapping and analysis purposes and consumed by the public through our web mapping services online.

Geospatial data management incorporates the organization and documentation of both file-based and server-based geospatial data. This needs to be a collaborative effort with GIS staff providing the lead through consultation on the best practices for organizing, storing, using, processing and documenting geospatial data, and GCMRC project staff adhering to protocols and best practices. Each project is unique, and how the geospatial data are organized is the responsibility of the principal investigator or another member of the project assigned as the data steward. This mostly speaks to file-based data (data stored in directories and folders). Server-based geospatial data are final versions of data sets stored within an Oracle Spatial Database. These are enterprise-level data sets that range from canyon-wide data collection missions (overflight imagery, digital surface models) to long-term monitoring efforts (site-based and reach-based topographic surveys) to more localized reference layers (Glen Canyon Fish Sampling Units). The GCMRC Oracle Spatial Database now contains over 3.5 terabytes of geospatial data, with more being added every year.

By leveraging the power of an Oracle database, very large data sets, such as 20-cm pixel resolution, 4-band (Red, Green, Blue, and Near-Infrared wavelengths) digital imagery for 300 miles of river, can be stored and served efficiently allowing for improved access to geospatial data by multiple users through many different avenues. While maintaining an Oracle database does come with some additional responsibility for GIS staff, the benefits by far outweigh the costs in terms of staff time. While the ease of access and improved performance alone would warrant using an enterprise system, the power of server-based data storage and retrieval is truly realized when considering how much utility is gained through this system. Data stored just once in an Oracle database can be accessed simultaneously on a local desktop computer, through GCMRC's web mapping applications, on a mobile device application, and through services to a remote computer. The effort devoted to building and improving upon this aspect of our data management capability will benefit most, if not all, projects and GCMRC as a whole.

Project Element 14.2.2. GIS Process and Data Set Documentation

Thomas M. Gushue, GIS Coordinator, USGS, GCMRC
Timothy Andrews, IT Specialist, USGS, GCMRC
TBD, Geographer (GS-09), USG, GCMRC

Senior GIS staff members will also be in charge of writing USGS Open-File Reports and possibly other published works that document geospatial data sets, GIS processes and other GIS-related applications developed for GCMRC. These published reports would follow the USGS peer and policy review process and provide the necessary, citable building blocks for other, more scientifically rigorous manuscripts developed by other projects. Currently, a need exists for researchers to be able to cite some of our most basic data sets, such as the GCMRC river mile system, within their own manuscripts.

Outcomes and Products – FY15

- The GCMRC Centerline and River Mileage Reference System. A published data series report on the methods and processes used to develop this system and the associated cross reference work with other known mile systems used for the Colorado River between Lake Powell and Lake Mead.

Outcomes and Products – FY16

- The GCMRC Colorado River Map Book. A data series/map series publication of GCMRC's most commonly used river map book developed by GIS staff as a field reference for scientific work conducted on the Colorado River in Grand Canyon. The map book to be published will contain many of GCMRC's geospatial data sets including most recent available overflight imagery (May 2013), GCMRC's river mile system, monitored and National Park System river campsites, river rapids, place names, and tributaries of the Colorado River. Peer and policy reviews will be required prior to making this mapping product more widely available.

Outcomes and Products – FY17

- The GCMRC Colorado River Fish Sampling Cross Reference System. A data series report on the methods used to develop a fish sampling system currently used by all mainstem sampling efforts, and how the cross reference relationships were built to join previously collected fish monitoring data associated with mainstem sampling.

Project Element 14.3.1. Access to Geospatial Data Holdings – The Geospatial Portal

Thomas M. Gushue, GIS Coordinator, USGS, GCMRC
Timothy Andrews, IT Specialist, USGS, GCMRC
TBD, Geographer (GS-09), USG, GCMRC

Along with the strides made in developing an enterprise-level GIS at GCMRC, new GIS services leveraging the Oracle Spatial Database have been deployed both internally for desktop

GIS users and through GCMRC's public-facing website to provided better access to more geospatial data holdings than ever before (Fig. 4). How geospatial data are stored and served is intimately tied to how users will access these data sets. Perhaps the most powerful aspect of using GIS services for disseminating data is the flexibility in how data can be packaged (a single service for an individual data set, multiple services containing many data sets within one map, time-enabled services, 3D services, etc.) and how these services can be consumed (desktop mapping applications, web page maps, website applications, mobile device applications, etc.). Geographic Information Systems services are the new currency for sharing geospatial data, and providing a single website for accessing these services is the next logical step for improving access to GCMRC's geospatial data holdings.

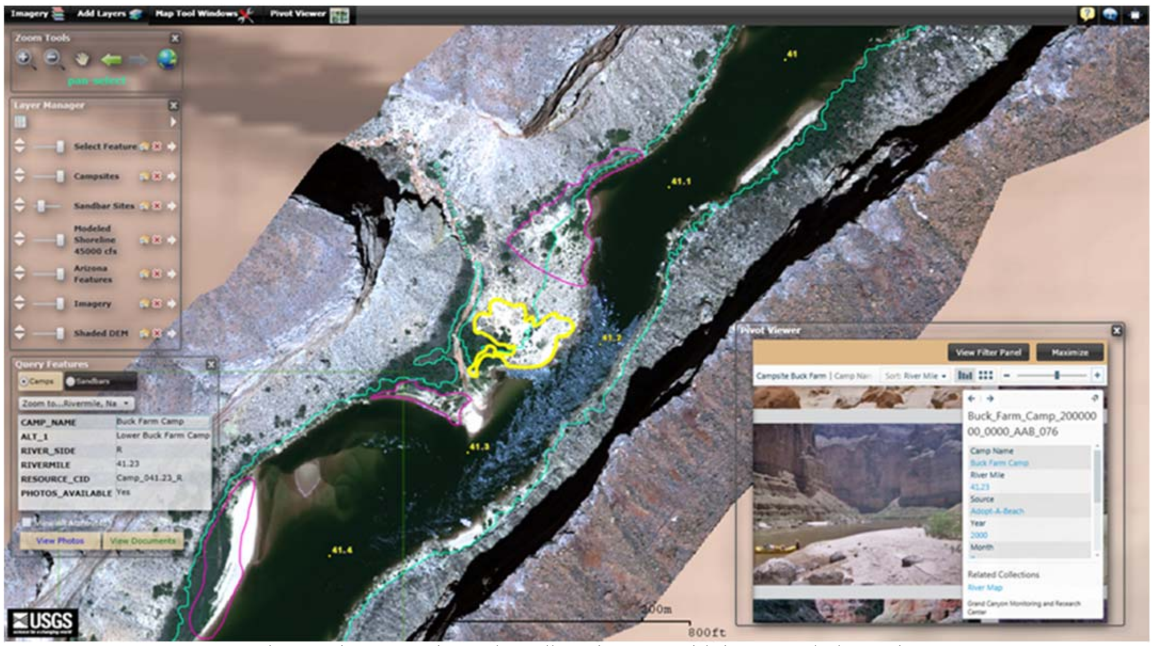

Figure 4. GCMRC's interactive campsite and sandbar site map with integrated photo viewer. Users can query campsite and sandbar site data sets, view related attributes, and launch available photo collections that offer thousands of on-site and remote camera photographs.

In 2014, a beta version Geospatial Portal is being designed and built that will streamline access to many of GCMRC's most frequently used and requested geospatial data sets. Ultimately, the Geospatial Portal will provide access to all of GCMRC's finished geospatial products. The Geospatial Portal builds on the existing Oracle-ESRI system architecture currently used by GCMRC for creating and sharing GIS Services, and so many of the components needed for the Geospatial Portal are already in place. The portal will provide access to maps, data sets, metadata, applications and other associated data through an organized, searchable interface. Services accessible through the portal will range from a basic map of where GCMRC projects conduct their field work to an application with interactive tools for analyzing sandbar changes over time to a map service that allows researchers to create and print their own field maps.

Ultimately, GCMRC project leads and outside cooperators will be able to share data through this system, pushing the Geospatial Portal beyond just a content delivery system into a truly collaborative tool. While it is anticipated that a development version of the Geospatial Portal will be available in FY15, it is likely that populating the portal with content will be an ongoing activity. Benchmarks for what is made available through the Geospatial Portal will be addressed as project-specific geospatial data sets are finalized.

Project Element 14.3.2. Access to Geospatial Data Holdings – ESRI's ArcGIS Online

Thomas M. Gushue, GIS Coordinator, USGS, GCMRC
Timothy Andrews, IT Specialist, USGS, GCMRC
TBD, Geographer (GS-09), USG, GCMRC

In FY13–14, GCMRC's GIS staff began using ESRI's online portal service for disseminating data to a much wider audience than ever before. This service, ArcGIS Online, has quickly become one of the most used geospatial content delivery systems available on the web. There are currently several GCMRC applications and data sets available through this online system (see Data Products section). In FY15–17, we plan to expand on the data made available to the public through this service. The benefit of using ArcGIS online in addition to hosting our own geospatial portal is that a particular service only needs to be created once by GIS staff, but can then be posted on both GCMRC's website and through ESRI's ArcGIS Online to reach a wider audience.

D.2 Personnel and Collaborations

The personnel required for this project includes two full-time senior (GS-12) GIS professionals and one full-time junior-level (GS-09) GIS professional. Geospatial data processing and analysis tasks performed specifically for other project elements are described and budgeted within those project descriptions (see Table 1 below for a listing of those project elements). Additionally, one half-time junior-level (GS-09) GIS professional will be assigned to GIS Services and Support project elements (14.2.2. and 14.3.2.).

D.3 Deliverables

See "Outcomes and Products" in Project Element 14.2.2.

E. Productivity from Past Work (during FY 13–14)

E.1. Data Products

List of existing Products (from FY13–14)

- Web Mapping Applications and Services available on GCMRC's website

Maps and Data Portal: http://www.gcmrc.gov/dasa/ (Fig. 5)

- GCMRC Interactive Campsite and Sandbar Map with Photo Viewer: http://www.gcmrc.gov/gis/silvermap1.aspx (requires Microsoft Silverlight)
- GCMRC Campsite Atlas Viewer: http://www.gcmrc.gov/gis/silveratlas1.aspx (requires Microsoft Silverlight)
- Grand Canyon River Campsites Tour: http://www.gcmrc.gov/gis/camptour/index.html (multiplatform, works on Windows, Mac, iOS, Android operating systems)
- Photo Viewer application: http://www.gcmrc.gov/gis/silverimage1.aspx (view thousands of sandbar and campsite photos, requires Microsoft Silverlight)

- Dual Photo Viewer application: http://www.gcmrc.gov/gis/silverdualpivot.aspx (view thousands of sandbar and campsite photos side-by-side for comparison, requires Microsoft Silverlight)

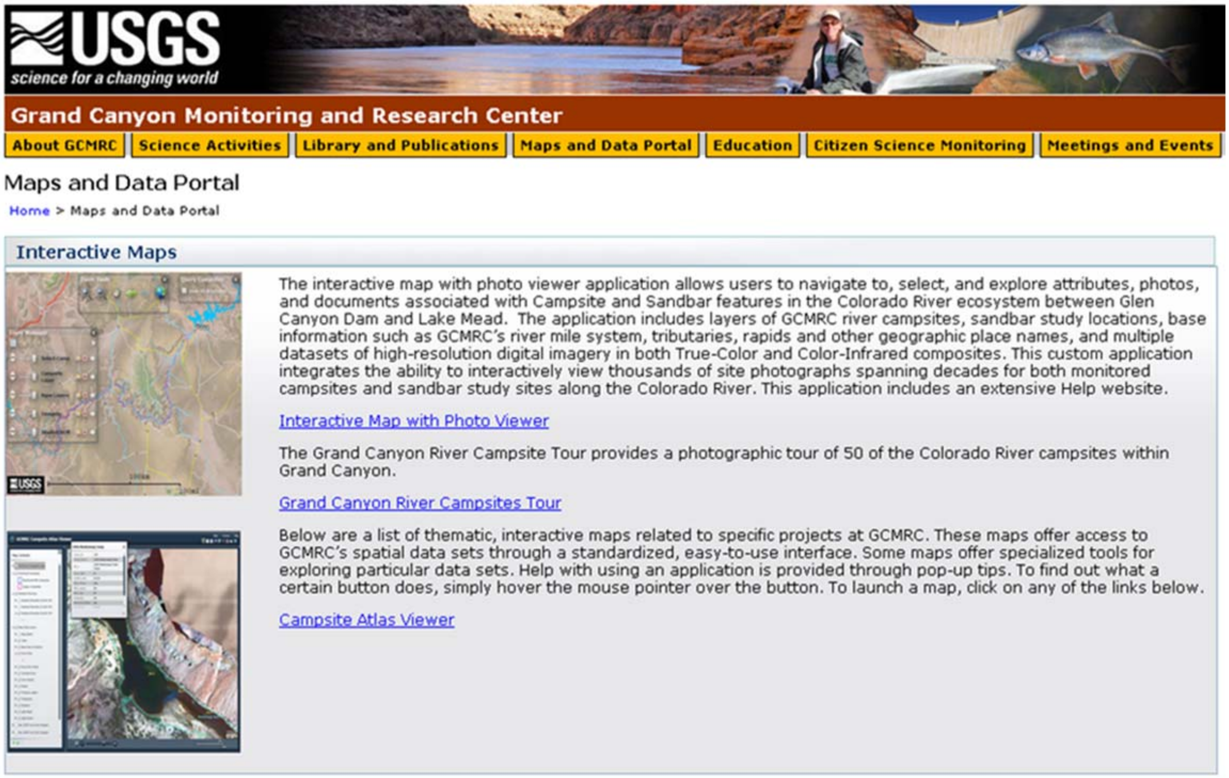

Figure 5. Sample image from GCMRC's website showing the Maps and Data Portal page.

Availability of GCMRC data and services on ESRI's http://www.arcgis.com/home/

- Digital imagery of the Colorado River corridor between Glen Canyon Dam and Lake Mead (2002, 2005, and 2009)
- 10-meter Digital Elevation Model (DEM) of the Grand Canyon basin
- Fine-grained Integrated Sediment Team (FIST) reach-based full channel topography (2000 – 2005)
- Sandbar deposition map tour web application following the HFEs of 2012 and 2013
- Campsite atlas map tour web application
- Grand Canyon base layers web mapping application

E.2. Presentations at GCDAMP meetings

- Development of a new web mapping and photo viewer application for the Grand Canyon Monitoring and Research Center, Poster presentation at GCDAMP Technical Work Group meeting, Phoenix, AZ, January 28, 2014.
- Extending sandbar monitoring back in time using photogrammetry, digital terrain extraction, and orthorectification of historical aerial imagery, Grand Canyon, Arizona, Poster presentation at GCDAMP Technical Work Group meeting, Phoenix, AZ, January 28, 2014.

- Low flows in Glen Canyon: preliminary geomorphic analysis of the potential effects on fish and food base, Presentation by T.S. Melis and others, at GCDAMP Technical Work Group meeting, Phoenix, AZ, January 28, 2014.
- Preliminary low-flows study in the Lees Ferry tailwater below Glen Canyon Dam, Poster presentation at GCDAMP Technical Work Group meeting, Phoenix, AZ, January 28, 2014.

E.5. Presentations at professional meetings

Development of a new web mapping and photo viewer application for the Grand Canyon Monitoring and Research Center, Poster presentation at ESRI UC Conference, July 2013, San Diego, CA

F. Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
X							14	Geographic Information Systems, Services, and Support	Gushue et al.	$171,300	$4,000	$17,400	$0	$0	$0	$30,100	$222,800
FY16																	
X							14	Geographic Information Systems, Services, and Support	Gushue et al.	$172,900	$6,000	$16,000	$0	$0	$0	$41,600	$236,500
FY17																	
X							14	Geographic Information Systems, Services, and Support	Gushue et al.	$179,300	$4,000	$16,000	$0	$0	$0	$54,600	$253,900

Table 1. A list of GIS planned support for FY2015–17 Triennial Work Plan

				Number of Pay Periods		
Project Title Name	**Project Number**	**GIS Staff**	**Project Element Title**	**FY15**	**FY16**	**FY17**
Sandbars and Sediment Storage Dynamics	3.1.2	Tom Gushue, GS-12	Monitoring sandbars and shorelines above 8,000 ft^3/s by remote sensing	2	1	1
Sandbars and Sediment Storage Dynamics	3.1.2	Geographer, GS-09	Monitoring sandbars and shorelines above 8,000 ft^3/s by remote sensing	2	3	3
Sandbars and Sediment Storage Dynamics	3.1.4	Tom Gushue, GS-12	Analysis of historical images at select monitoring sites	4	4	4
Sandbars and Sediment Storage Dynamics	3.1	Tim Andrews, GS-12	Sandbar Monitoring	1	1	1
Connectivity along the fluvial-aeolian-hillslope continuum	4.2	Tim Andrews, GS-12	Monitoring of cultural sites in Grand and Marble Canyons	4	4	4
Foobase Monitoring and Research	5.1.1 5.2	Geographer, GS-09	Insect emergence in Grand Canyon via citizen science; Patterns and controls of aquatic drift	2	2	2
Foobase Monitoring and Research	5.2	Tim Andrews, GS-12	Patterns and controls of aquatic drift	4	4	4
Mainstem Colorado River humpback chub aggregations	6.1	Tom Gushue, GS-12	Monitoring humpback chub aggregation relative abundance and distribution	2	2	1
Mainstem Colorado River Humpback Chub Aggregations	6.1 6.2 6.7	Geographer, GS-09	Mainstem Colorado River humpback chub aggregations and fish community dynamics (four elements supported)	1	2	2
Mainstem Colorado River Fish Community Dynamics	6.4	Geographer, GS-09	System-wide Electrofishing	1	2	3
Population Ecology of Humpback Chub in LCR	7.1	Geographer, GS-09	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	1	2	3
Population Ecology of Humpback Chub in LCR	7.2 7.3 7.5	Geographer, GS-09	Juvenile Chub Monitoring in the mainstem near LCR; July LCR juvenile humpback chub marking; Food web monitoring in the Little Colorado River.	2	2	2
Population Ecology of Humpback Chub in LCR	7.3	Tim Andrews, GS-12	GIS software development for field mapping and data entry applications	2	2	2
Population Ecology of Humpback Chub in LCR	7.4	Tim Andrews, GS-12	Remote PIT tag array monitoring	3	3	3
Rainbow Trout in Glen and Marble Canyons	9.1 9.2	Tom Gushue, GS-12	Lees Ferry Rainbow Trout Monitoring; Detection of Rainbow Trout Movement	2	2	1
Rainbow Trout in Glen and Marble Canyons	9.9	Tom Gushue, GS-12	Effects of High Flow Experiments on Rainbow Trout Population Dynamics	2	2	2
Rainbow Trout in Glen and Marble Canyons	9.1 9.9	Geographer, GS-09	Lees Ferry Rainbow Trout: Monitoring, Analysis, and Study Design; Effects of High Flow Experiments on Rainbow Trout Population Dynamics	1	1	1
Mapping Flow Inundation of Shoreline Areas and Bed Textures	10.1	Tom Gushue, GS-12	Refine Hummingbird Sidescan Sonar and other Channel Mapping Methods to Support Fish and Foodbase Research	3	4	4

Mapping Flow Inundation of Shoreline Areas and Bed Textures	10.1	Geographer, GS-09	Refine Hummingbird Sidescan Sonar and other Channel Mapping Methods to Support Fish and Foodbase Research	2	2	2
Riparian Vegetation Monitoring and Analysis	11.1	Geographer, GS-09	Project Element 11.1. Ground-based Vegetation Monitoring	1	0	0
GIS Services and Support	14.2.1	Tom Gushue, GS-12	Geospatial Data Management	4	5	5
GIS Services and Support	14.2.1	Geographer, GS-09	Geospatial Data Management	7	5	4
GIS Services and Support	14.2.2	Tom Gushue, GS-12	GIS Process and Data Set Documentation	5	4	4
GIS Services and Support	14.2.2	Geographer, GS-09	GIS Process and Data Set Documentation	6	5	4
GIS Services and Support	14.2.2	Tim Andrews, GS-12	GIS Process and Data Set Documentation	6	5	5
GIS Services and Support	14.2.2	SBSC Geographer, GS-09	GIS Process and Data Set Documentation	5	5	5
GIS Services and Support	14.3.1 14.3.2	Tom Gushue, GS-12	Access to Geospatial Data Holdings	4	4	6
GIS Services and Support	14.3.1 14.3.2	Tim Andrews, GS-12	Access to Geospatial Data Holdings	6	5	5
GIS Services and Support	14.3.1 14.3.2	SBSC Geographer, GS-09	Access to Geospatial Data Holdings	8	8	8

Project 15. Administration

Initiall Estimate: FY15: $1,298,500; FY16: $1,432,700; FY17: $1,556,300

GCDAMP Funding: FY15: $1,298,500; FY16: $1,332,400; FY17: $1,478,500

The USGS Administration budget covers salaries for the communications coordinator, the librarian, and the budget analyst for GCMRC, in addition to monetary awards for all GCMRC personnel. The vehicle section covers GSA vehicle costs including monthly lease fee, mileage costs, and any costs for accidents and damage. DOI vehicles are also included in this section of the budget to pay for vehicle gas, maintenance, and replacements costs. Leadership personnel covers salary for the GCMRC Chief and Deputy Chief, half the salary for two program managers, and some of the travel and training costs for these personnel. AMWG/TWG travel covers the cost of GCMRC personnel to travel to the AMWG and TWG meetings. SBSC Information Technology (IT) overhead covers GCMRCs IT equipment costs. Logistics base costs covers salaries and travel/training. These base costs also include a $35,000 contribution to the equipment and vehicles working capital fund.

Budget

Monitoring		Research															
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
										FY15							
							15	**Administration and Support**		**$770,600**	**$35,000**	**$227,000**	**$20,000**	**$79,000**	**$0**	**$166,900**	**$1,298,500**
X							15.1	GCMRC Admin and Support		$511,300	$30,000	$227,000	$20,000	$79,000	$0	$125,600	$992,900
X							15.2	GCMRC logistical support		$259,300	$5,000	$0	$0	$0	$0	$41,300	$305,600
										FY16							
							15	**Administration and Support**		**$827,700**	**$37,500**	**$226,500**	**$20,000**	**$81,500**	**$0**	**$239,500**	**$1,432,700**
X							15.1	GCMRC Admin and Support		$563,200	$32,000	$226,500	$20,000	$81,500	$0	$181,900	$1,105,100
X							15.2	GCMRC logistical support		$264,500	$5,500	$0	$0	$0	$0	$57,600	$327,600
										FY17							
							15	**Administration and Support**		**$847,900**	**$40,000**	**$246,000**	**$20,000**	**$84,000**	**$0**	**$318,400**	**$1,556,300**
X							15.1	GCMRC Admin and Support		$578,100	$34,000	$246,000	$20,000	$84,000	$0	$242,900	$1,205,000
X							15.2	GCMRC logistical support		$269,800	$6,000	$0	$0	$0	$0	$75,500	$351,300

Appendices

Appendix 1 references Project 1, which is funded through a different account.

Appendix 2-A summarizes the source of funding for each project element for the FY15 budget. Project elements for which no funding source has presently been identified are listed.

Appendix 2-B summarizes the categories for the FY15 budget. A budget summary for each project element is described. The category for “non-USGS cooperators” includes universities, consulting firms, sister agencies of the federal government, and agencies of state government. The category for “USGS cooperators” includes various science centers of the USGS located in Arizona, California, and Wisconsin. Investigators and their affiliations are described in each project description.

Appendix 2-C summarizes the categories for the FY16 budget. A budget summary for each project element is described. The category for “non-USGS cooperators” includes universities, consulting firms, sister agencies of the federal government, and agencies of state government. The category for “USGS cooperators” includes various science centers of the USGS located in Arizona, California, and Wisconsin. Investigators and their affiliations are described in each project description.

Appendix 2-D summarizes the categories for the FY17 budget. A budget summary for each project element is described. The category for “non-USGS cooperators” includes universities, consulting firms, sister agencies of the federal government, and agencies of state government. The category for “USGS cooperators” includes various science centers of the USGS located in Arizona, California, and Wisconsin. Investigators and their affiliations are described in each project description.

Appendix 3 lists logistics and schedules for all river trips and field work.

Appendix 4 lists key TWG guidance on how the Triennial Work Plan was prepared.

Project 1. Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring

Initial Estimate: FY15: $20,600; FY16: $0; FY17: $0

GCDAMP Funding: FY15: $20,600; FY16: $0; FY17: $0

Other BoR Funding: FY15: $289,100; FY16: $310,500; FY17: $333,200

A. Investigators

William S. Vernieu, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

B. Project Summary

This project conducts water-quality monitoring on Lake Powell and the Glen Canyon Dam tailwaters. The water-quality monitoring program consists of monthly surveys of the reservoir forebay and tailwater, as well as quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms. Water temperature, specific conductance, dissolved oxygen, pH, redox potential, turbidity, and chlorophyll concentration are measured throughout the water column at up to 30 sites on the reservoir (fig. 1), with samples for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton being collected at selected sites. The project also includes continuous monitoring of Glen Canyon Dam releases for water temperature, specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll concentration and monthly sampling for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton below the dam and at Lees Ferry.

The data collected by the project describe the current water quality of Glen Canyon Dam releases to the downstream ecosystem, as well as describe the current water-quality conditions and hydrologic processes in the Lake Powell reservoir, which can be used to predict the quality of future releases from the dam.

It is proposed that the existing water-quality monitoring program will continue through the FY15–17 period at its current level. The Seabird CTD instrument will continue to be used as the primary profiling device for reservoir stations. Minor changes may be made to the existing program in terms of number of stations sampled and the amount and type of samples collected. Recent data collected from the monitoring program will continue to be published and an interpretive synthesis of existing data will be developed for publication during the FY15–17 period.

Physical and chemical information from this program was published as Data Series Report DS-471 (Vernieu, 2013). An updated revision to this report is currently in development. Biological data will be published in a separate data series report, currently in review. These reports will be combined in future revisions. All information from this program is currently stored in the Microsoft Access water-quality database (WQDB).

It is also proposed that a system for online data access and dissemination will be developed during this period. This will involve migration of the current WQDB database into an Oracle database to enhance online data availability. A web site will then developed that will allow access to currently available data and the interactive display of various graphic products depicting summarized data collected by the program through a map-based user interface. Some aspects of data management and the development of visualization tools will be made in-house, while other products will be developed in collaboration with other USGS offices such as the Wisconsin Science Center's Wisconsin Internet Mapping office (WiM) (http://wi.water.usgs.gov/wim/) or the Center for Integrated Data Analytics (CIDA) (http://cida.usgs.gov/).

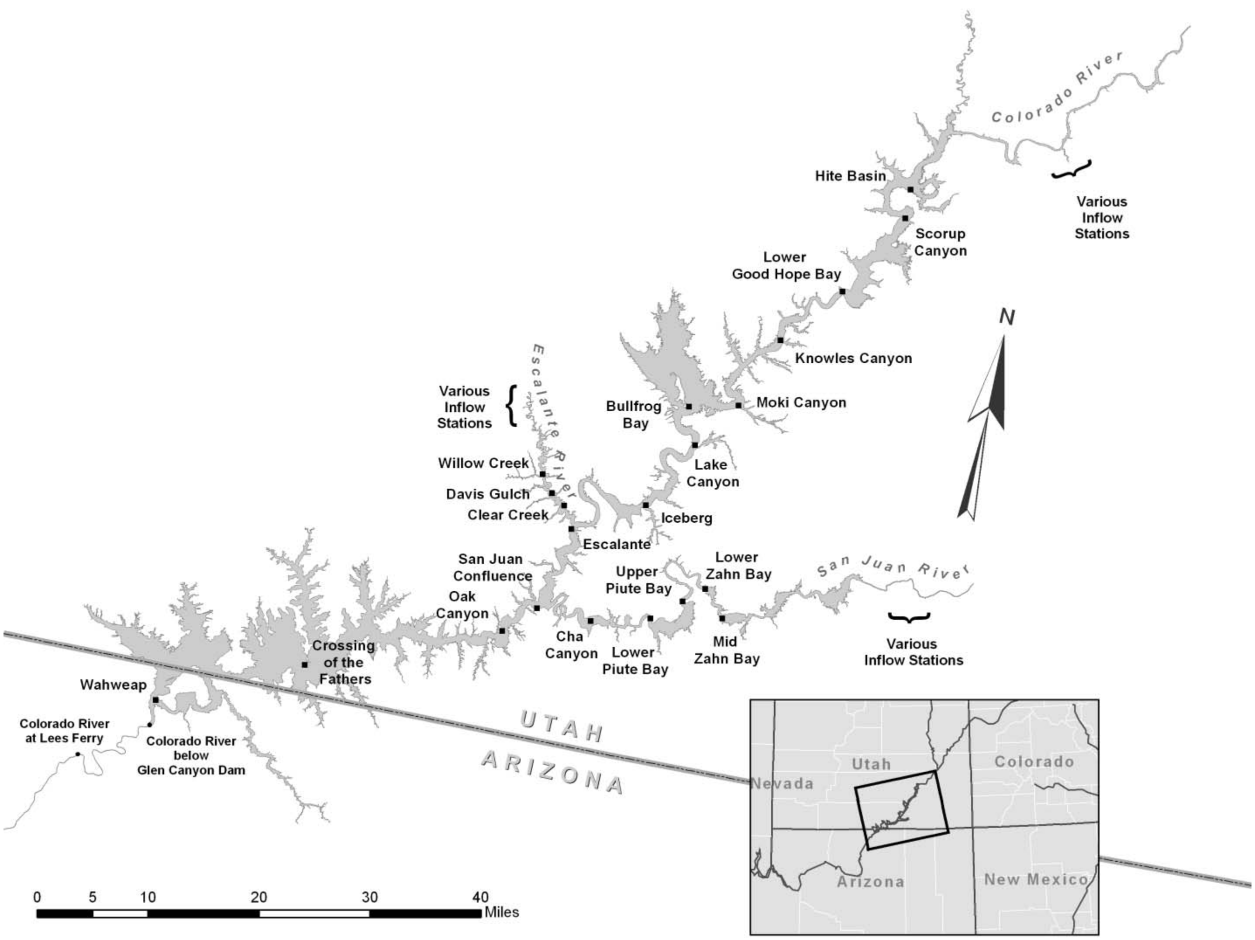

Figure 2. Lake Powell water-quality monitoring locations.

The USGS Grand Canyon Monitoring and Research Center (GCMRC) will work collaboratively with the Bureau of Reclamation (BOR) in efforts to enhance simulation modeling of Lake Powell Reservoir water quality and limnology. Modeling will utilize the CE-QUAL-W2 model, a 2D water quality and hydrodynamic model, currently maintained by BOR. This model is currently used to project Glen Canyon Dam release temperatures, and will be enhanced to answer various research questions relating to the fate of inflow currents, effects of reservoir drawdowns, and dissolved oxygen dynamics in the reservoir.

The Lake Powell monitoring program continues to be directed and administratively managed by GCMRC, with cooperation and sole funding provided by BOR under Interagency Agreement No. R13PG40028, effective through December 31, 2017.

C. Background

C.1. Scientific Background

Lake Powell is formed by impoundment of the Colorado River by Glen Canyon Dam, which was completed in 1963 and receives the combined inflows of the Colorado, Green, San Juan, Escalante, and Dirty Devil rivers. The reservoir is stratified vertically according to density into different layers with varying water-quality characteristics. This stratification is the primary determinant of the quality of water released from Glen Canyon Dam and also affects physical, chemical, and biological characteristics of other portions of the reservoir.

Two main mixing processes take place in Lake Powell. Convective mixing is the cooling of surface waters in winter months, which increase in density and mix with deeper waters in the upper layers of the reservoir as winter progresses. This results in a well-mixed surface layer, or epilimnion, that extends to the penstock withdrawal zone in early winter and begins to influence Glen Canyon Dam releases, resulting in the warmest water released from the dam. Advective mixing results from the horizontal flow of water through the reservoir. Seasonal differences in the density of inflow currents determine the depth at which this water moves through the reservoir and its interaction with existing reservoir waters. The largest volume of water enters the reservoir from spring snowmelt runoff and represents the water with the least density entering the reservoir. This runoff plume travels through the reservoir near the surface and influences the most biologically active layers of the reservoir. In contrast, winter inflows represent water of the greatest density entering the reservoir and plunge to deeper depths as they enter the reservoir. When densities are sufficient to cause a bottom underflow throughout the length of the reservoir, this fresher water displaces older water in the deepest portions of the reservoir upward. When winter inflows are of insufficient density to travel as a bottom underflow, they flow into intermediate layers of the reservoir and leave the deepest portions of the reservoir stagnant, which can lead to a loss of dissolved oxygen. The conditions that result in a bottom underflow, as opposed to an interflow, are currently poorly understood. Application of the CE-QUAL-W2 model can help address this question by running multiple scenarios of inflow and meteorological conditions and evaluating the resultant fates of these inflow currents.

Reservoir drawdown and the fate of these inflow current can have a substantial effect on the water-quality conditions of the reservoir forebay and Glen Canyon Dam releases. Throughout the history of Lake Powell, there have been several extended drought periods that have been characterized by lower inflow volumes to the reservoir, compared to reservoir release volumes, resulting in a reduction in reservoir storage and a drawdown of surface elevations. Through most of the past decade, the Colorado River basin has experienced drought conditions, which resulted in the drawdown of the reservoir to a minimum of 3,555 ft in 2005. This resulted in the warmer surface layers being closer to the penstock withdrawal elevation and caused release temperatures to increase to a maximum of 16°C in October 2005, more than 6°C above normal for that period. Release temperatures have been above normal from 2003 through 2013 as the reservoir remained at elevations below 3,640 ft, with the exception of 2011 in which the reservoir reached an elevation of 3,660 ft. In the spring of 2014, Lake Powell reached a surface elevation of 3,575 ft, its second lowest elevation since the reservoir first filled in 1980. Increased temperatures and possible reductions in dissolved oxygen concentrations in Glen Canyon Dam releases are expected in the fall of 2014.

Lake Powell receives an average of approximately 30,000 acre feet of sediment per year (Ferrari, 1986), most of which forms deltaic sediment deposits in the inflow areas of the reservoir. As reservoir elevations fluctuate, these deposits are resuspended and moved further downstream into the reservoir. Because of oxygen demand from decaying organic matter in the delta sediments, inflows traveling through the exposed delta become depleted in oxygen concentrations. With low reservoir elevations, these hypoxic waters can influence dam releases, which can cause adverse conditions in the aquatic ecosystem below Glen Canyon Dam. In 2005, the inflow plume had a minimum dissolved oxygen concentration of 1.7 mg/L and resulted in a dissolved oxygen concentration in Glen Canyon Dam releases of 3.6 mg/L in October 2005.

Reservoir drawdown may also cause the release of nutrients from deltaic deposits and may act to enhance the biological characteristics of the reservoir. If further reductions to reservoir inflows occur in the future in response to a changing climate, these reservoir drawdown scenarios may become more common. An increased understanding of the effects of various factors such as reservoir elevation, inflow volume, age and oxygen demand of delta sediments on Glen Canyon Dam releases would be gained by applying the CE-QUAL-W2 model to determine the relative effects of these factors and would result in increased capabilities in predicting and mitigating adverse effects to the downstream ecosystem.

As delta deposits are resuspended, they are also redeposited as they enter the reservoir, resulting in the overall movement of the sediment deltas farther downstream under drawdown conditions. Although the 2014 low reservoir elevation of 3,575 ft was approximately 20ft higher than its 2005 low elevation of 3,555 ft, sediment deltas extended 2.5, 1.4, and 0.5 km farther downstream on the Colorado, San Juan, and Escalante arms of the reservoir, respectively, than they did in 2005. In some areas of the reservoir, major landslide deposits in the main channel of the reservoir can act as underwater dams that block sediment from moving further downstream.

C.2. Management Background

BOR initiated a water-quality monitoring program on Lake Powell starting in 1964, which has continued to the present, to gather information to describe water-quality conditions and to observe changes in water quality as the reservoir filled and matured. Four distinct phases of monitoring activity have been identified, based on sampling frequency, spatial resolution of measurements, and changes in instrumentation.

Studies related to Lake Powell were conducted in the 1970s by educational consortiums and Federal and State agencies on topics that include sedimentation, circulation patterns, trace-element chemistry, remote sensing, and public-health issues (Potter and Drake, 1989). Various agencies and institutions have conducted additional research and monitoring during Lake Powell's recent history (Hart and Sherman, 1996; Marzolf, 1998; Hart, and others, 2005).

Since 1996, the Lake Powell water-quality monitoring program has been administered and conducted by GCMRC. While coordinating with GCMRC investigators and addressing the information needs of the Glen Canyon Dam Adaptive Management Program (GCDAMP), funding for the Lake Powell monitoring program is provided solely by BOR, through Colorado River Storage Project power revenues. In 2013, a five-year Interagency Agreement (No. R13PG40028) for Lake Powell monitoring was initiated between BOR and GCMRC and is effective through December 31, 2017.

C.3. Key Monitoring and Research Questions Addressed in this project

The Lake Powell monitoring program is designed to address the status and trends of the water quality in Lake Powell and Glen Canyon Dam releases over a varying time scales as affected by hydrology, meteorology, climatology, and dam operations. The key components of reservoir and release water quality the monitoring program addresses include:

1. Characterization of the quality of Glen Canyon Dam releases immediately below Glen Canyon Dam and at Lees Ferry.
2. Characterization of the water quality of the forebay area immediately upstream from Glen Canyon Dam, immediately available for release.
3. Characterization of the water quality of the three major tributary arms of the reservoir to determine fate of inflow currents moving through the reservoir and their potential for release entrainment.
4. Determining ionic makeup of release and reservoir waters as an indicator of the origin of reservoir waters and overall Colorado River salinity patterns.
5. Determining nutrient concentrations of release and reservoir waters for their support of primary productivity in the reservoir and tailwater.
6. Determination of chlorophyll concentrations in release and reservoir waters and characterization and quantification of the biological community structure.

Several key research questions have developed from observations generated by the monitoring program. These include:

1. What determines the fate of reservoir inflow currents that promote mixing of the deeper portions of the reservoir near Glen Canyon Dam?
2. How do fluctuations in inflow volumes, reservoir storage, and surface elevation affect the quality of water moving past the tributary inflow deltas and through the reservoir and the potential for their influence on reservoir releases?
3. How do nutrient concentrations affect the primary production of the reservoir and tailwater, compared to other factors such as light availability and water temperature?
4. How will the establishment of quagga mussel populations affect nutrient concentrations and planktonic community structure?
5. How do underwater landslide deposits act to impede flows of density currents through the reservoir or trap suspended sediments?

Fate of Inflow Currents

Reservoir simulation modeling has the potential to address several of the research questions related to reservoir hydrodynamics and the water quality in Lake Powell and Glen Canyon Dam releases. The CE-QUAL-W2 is currently being used to predict temperatures of Glen Canyon Dam releases for the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement currently in development. However, additional development of the model is possible to provide better predictive capabilities earlier in time with improved inflow and meteorological monitoring. The model also has the capabilities to model dissolved oxygen concentrations, as well as other parameters such as nutrients and plankton, but the model has not been calibrated to do so. Improvement of inflow and meteorological monitoring and calibrations of the model for dissolved oxygen, nutrients, and plankton will improve the model’s effectiveness.

One of the most important processes in maintaining dissolved oxygen concentrations in the deepest portions of the reservoir is the travel of high density water currents through the reservoir during the winter. Normally, winter inflows are of sufficient density and volume to travel along the bottom of the reservoir and reach the dam in the early spring. This displaces pre-existing water in the hypolimnion upward for entrainment in dam releases and freshens the water in the deepest portion of the reservoir. However, in some years, the inflows are not of sufficient density to flow along the entire bottom of the reservoir and may travel through the reservoir in intermediate layers, leaving deeper portions of the reservoir stagnant and hypoxic. The conditions that dictate the fate of this inflow current are poorly understood at present. Simulation modeling of various winter inflow scenarios may be beneficial in identifying what factors are most important in determining the fate of these inflow currents.

Quality of Advective Inflows

The magnitude of inflow volumes, combined with reservoir elevations, determines how much resuspension occurs in the sediment deltas of the reservoir. Depending on the amount of organic material in the deltaic sediments and the resultant oxygen demand, a significant amount of dissolved oxygen can be removed from these currents. The actual effect of these currents on release water-quality depends on the volume of these currents moving through the reservoir and the amount of mixing or dilution with other reservoir water.

Nutrient Effects on Primary Production

Primary production is the synthesis of biomass by photosynthetic organisms, usually microscopic alage, or phytoplankton, in the reservoir. Secondary production is the generation of biomass from consumers of photosynthesizing organisms, such as zooplankton and higher trophic forms. In the presence of adequate light availability and water temperatures, nutrient concentrations are the primary determinants of primary productivity processes in Lake Powell and the Glen Canyon Dam tailwater. In general, concentrations of phosphorus compounds are relatively low in Lake Powell, which may indicate that phosphorus is a limiting nutrient in the reservoir in comparison to nitrogen compounds. Concentrations of both types of compounds in Lake Powell are mediated by primary production and are higher in deeper portions of the reservoir that have little or no light availability but continue to receive decomposing organic material from shallower depths. Concentrations of these compounds in Glen Canyon Dam releases fluctuate seasonally and could influence primary production in the tailwater below Glen Canyon Dam.

Effects on Quagga Mussel Establishment

Reproducing populations of quagga mussels (*Dreissena rostriformis bugensis*) have now been identified in Lake Powell. Subsequent monitoring of plankton populations will provide an excellent opportunity to determine the effects of this invasion on the biological resources of Lake Powell by comparison to the existing pre-invasion dataset of plankton abundance and community structure. A compilation of biological data through 2009 is slated for publication in 2014. In addition, a contract is now in place for the analysis of a large backlog of plankton samples collected through 2014. All backlogged samples have been submitted for analysis; these analyses are expected to be completed by early 2015. Data from these analyses will be incorporated into the WQDB database and published as part of an annual comprehensive data report, which will combine the biological data with existing chemical and physical data. This information will also be available through interactive online queries once the Lake Powell portion of the GCMRC website is developed.

Sediment Deposition Patterns

As the reservoir ages, the major tributaries of the Colorado, San Juan, and Escalante rivers continue to add sediment and reduce capacity of the reservoir with most sedimentation occurring in the inflow areas of the tributary arms as delta deposits. Reservoir drawdown processes remobilize these deposits, moving them further downstream in the reservoir basins. Large landslide deposits are present in the major tributary arms of the reservoir and can act to prevent further downstream movement of sediment. They can also cause localized water-quality problems in some areas of the reservoir. Two large landslide deposits in the Escalante arm of the reservoir are now, acting as underwater weirs, and limit hypolimnetic circulation, above these areas. This phenomenon results in low dissolved oxygen concentrations and presents an opportunity for simulation modeling to replicate these conditions and identify factors that promote or mitigate the development of these conditions.

D. Proposed Work

D.1. Project Elements

Monitoring

It is proposed the Lake Powell monitoring program continue in its present structure, consisting of monthly surveys of the reservoir forebay and tailwater, as well as quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms. Depth profiles of water temperature, specific conductance, dissolved oxygen, pH, oxidation-reduction potential, turbidity, and chlorophyll concentration are measured throughout the water column at up to 30 sites (fig. 1) on the reservoir, with samples for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton being collected at selected sites. Continuous monitoring of Glen Canyon Dam releases for water temperature, specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll concentration and monthly sampling for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton below the dam and at Lees Ferry, will also be maintained.

Data Access and Availability

To ensure data collected by the Lake Powell monitoring program is readily accessible to stakeholders, researchers, and the general public in a timely manner, the development of a website with online data access capabilities is proposed as a necessary component of the monitoring program. Data are already stored effectively in the Microsoft Access WQDB database, have been published as a USGS Data Series Report, and are available for download in database and csv format. However, the ability to query selected data, view graphical analyses of these queries, and serve other products through an interactive web-based interface is currently lacking. It is proposed that a system with these capabilities be developed and implemented early in the proposal period.

This project would first entail migration of the existing database to an Oracle-based database so that it would be for use by GCRMC staff to provide functionality equal to, or better than the existing database system. Since the existing database is already normalized and fully functional migration is expected to be fairly straightforward and can be accomplished in-house. Migration would consist of the following steps:

1. Migration of existing field definitions, table structure and metadata
2. Migration existing queries, data-entry forms, and reports
3. Transfer of the contents of each table in the database
4. Establishing procedures for incorporation of new data by manual or automated methods
5. Develop interfaces to various analytical software tools such as SAS, Surfer, Arc Map, and Microsoft Office products
6. Testing and quality assurance verification

To facilitate online access by stakeholders, managers, and other interested users, a website will also be developed that would serve as a primary point of access for information relating to the Lake Powell water-quality monitoring program. This site would allow interactive access to the database in the form of a map-based query system that would serve data from the various components of the monitoring program based on selected locations and time ranges. From these queries, users would be able to retrieve tabular data, statistical summaries of these data, and graphical depictions of depth profiles and the results of chemical and biological sample analyses at various time scales ranging from recent data to the entire historical record.

The development of the website and associated visualization tools will be developed in collaboration with other USGS offices such as the Wisconsin Science Center's Wisconsin Internet Mapping office (WiM) (http://wi.water.usgs.gov/wim/) or the Center for Integrated Data Analytics (CIDA) (http://cida.usgs.gov/).

Data products would include summary graphs and tables showing Lake Powell reservoir elevations and 24-month projections, Glen Canyon Dam release water quality, selected reservoir depth profiles, and isopleth figures displaying temperature, conductivity, dissolved oxygen or other parameters for the entire reservoir at a single point in time or as a time series for a given station.

At its full development, data from other sources would be available on the website, including:

1. reservoir elevation and storage information for other upper and lower Colorado River Basin reservoirs provided by BOR
2. streamflow and water-quality information for inflows from tributaries to Lake Powell from the USGS NWIS system
3. other Lake Powell data collected outside the existing GCMRC monitoring program
4. water-quality information collected on other reservoirs such as Lake Mead, Flaming Gorge, Navajo, and other reservoirs provided by BOR, Southern Nevada Water Authority, and other agencies or academic institutions.
5. links to other data sources and relevant publications.

The development of the website, map-based user interface, and associated visualization tools would be accomplished by a combination of in-house efforts and assistance from other USGS offices such as the Wisconsin Science Center's Wisconsin Internet Mapping office (WiM) (http://wi.water.usgs.gov/wim/) or the Center for Integrated Data Analytics (CIDA) (http://cida.usgs.gov/). Under the existing Interagency Agreement with BOR, funds have been allocated for the work of Dale Robertson of the Wisconsin Science Center. This funding would be used for initial development of the website, map-based user interface, visualization tools, depending on the actual distribution of work between GCMRC and other USGS entities.

Modeling

Simulation modeling of Lake Powell water quality and hydrodynamic patterns is currently being conducted by BOR's Upper Colorado Regional Office using the Army Corps of Engineers CE-QUAL-W2 model. The CE-QUAL-W2 model is a two-dimensional (longitudinal and vertical), laterally averaged, finite-difference water-quality and hydrodynamic model for rivers, estuaries, lakes, reservoirs and river basin systems. It was originally known as LARM (Laterally Averaged Reservoir Model), developed by Edinger and Buchak (1975). In its early stages, The LARM model was applied to Lakes Powell and Mead, (Edinger and Buchak, 1982; Edinger and others, 1984). Current model release enhancements have been developed under research contracts between the Army Corps of Engineers and Portland State University under supervision of Dr. Scott Wells (2000). Williams (2007) applied the CE-QUAL-W2 model to Lake Powell and developed an initial dissolved oxygen calibration for the model.

GCMRC provides data and collaboration with the development of the model for calibration and verification. The model has been calibrated and verified to simulate historical patterns of temperature and salinity in Glen Canyon Dam releases. Dissolved oxygen is also being simulated; however, some additional effort is needed for final calibration and verification. This model can be used to synthesize data for periods in which regular monitoring was not conducted and to simulate the effects of various hypothetical operational, hydrological, and climatological scenarios on historical patterns. It is also used to provide predictions of future temperature and dissolved oxygen patterns in Glen Canyon Dam releases. One major shortcoming of the model's predictive capabilities is the lack of adequate input data for inflow water quality and meteorological conditions in the upstream portion of the reservoir. The error in predictive capability decreases substantially with the input of data from reservoir monitoring in the early summer.

Opportunities exist for further understanding of reservoir processes by model development and enhancement. The use of this model, calibrated for temperature, nutrients, and biological components, to reconstruct historical conditions, project future hydrological and climatic scenarios, and simulate the response of the system to hypothetical reservoir operations could help to answer a variety of research questions and gain further understanding of the various hydrodynamic, chemical, biological, and mixing processes in the reservoir.

GCMRC will work on a collaborative basis with BOR to calibrate the model for dissolved oxygen, nutrient dynamics, and biological responses under a collaborative system in which current capabilities of the CE-QUAL-W2 model are maintained, while the research-related capabilities of the model, such as the forecasting of low dissolved oxygen concentrations in Glen Canyon Dam releases under reservoir drawdown and identifying factors that affect the fate of inflow currents. It is proposed the model be maintained for its current purposes by BOR, with further development by GCMRC, a post-doctoral fellow, or an outside contractor, such as Ed Buchak, who has performed previous work for BOR.

Biological Data Analysis

As data from a backlog of plankton samples become available within the next year, a complete history of Lake Powell plankton data, including the initial stages of a quagga mussel invasion, will become available for analysis. When complete, it is proposed that the biological data be incorporated in regular reporting with physical-chemical data. An analysis of these data would include identifying trends in biomass and community structure of zooplankton and phytoplankton populations and identifying potential factors that affect these populations.

Sediment Delta Monitoring

Since 1998, longitudinal sonar depth measurements of the sediment deltas in Lake Powell tributaries have been recorded on thermal chart paper, in conjunction with quarterly reservoir water-quality surveys. Digitization of these charts yields a longitudinal profile of the elevation of the sediment delta with respect to distance along the original river channel. Collectively, these profiles provide a history of Lake Powell sediment deposition during this period, over a range of reservoir elevations and inflow volumes. Information from this record demonstrates sediment transport and deposition processes as affected by inflow currents, underwater landslides, and other channel obstructions and can help to explain unusual water-quality conditions observed in portions of the reservoir.

Digitization of these profiles was initiated in 2012, with the aid of a temporary student intern. Progress has stalled since the departure of that intern and lack of additional staffing. With the addition of a technician to the GCMRC staff, it is proposed that remaining profiles be digitized, compiled, and published as a complete historical record.

D.2 Personnel and Collaborations

Funding for the Lake Powell water-quality monitoring program is provided directly by BOR; no GCDAMP funds are used for this project. In addition to direct funding, BOR also provides field support staff for quarterly reservoir surveys, chemical sample analysis through its Lower Colorado Regional Laboratory, plankton sample analysis through contract, and maintains the Seabird SBE19plusV2 CTD profiling instrument. The National Park Service provides a 0.5 FTE field technician, also funded by BOR. GCMRC participates in the Lake Powell Cooperators Group, a group of federal, state, and academic researchers, tribal representatives, concessionaires, recreational organizations, and members of the general public with interests in scientific activities conduction on Lake Powell. The National Park Service hosts annual meetings of the Lake Powell Cooperators Group to present and discuss current monitoring activities and findings, and coordinate future activities.

Dr. Dale Robertson, of the USGS Wisconsin Science Center, has been collaborating with the Lake Powell program to assist with data interpretation and modeling and to develop an interpretive synthesis of the published data. This synthesis will describe the physical, chemical, and biological characteristics of Lake Powell and Glen Canyon Dam releases compared to climatological factors and various aspects of dam operations. Available meteorological, hydrological, and limnological data will be used to improve, document, and verify the existing CE-QUAL-W2 model for Lake Powell, in collaboration with BOR scientists. The model will then be used to better understand the changes that have occurred in Lake Powell, predict future changes in response to climate change, and verify interpretive hypotheses.

We propose to collaborate with the Wisconsin Science Center's Wisconsin Internet Mapping office (WiM) (http://wi.water.usgs.gov/wim/) or the Center for Integrated Data Analytics (CIDA) (http://cida.usgs.gov/) to assist with migration of the current database to an Oracle platform, to develop tools for data retrieval, summary, and analysis, and to develop a web-based interface to allow access to data and display of graphical products. In addition, GCMRC will become more closely involved with the USGS Community for Data Integration to share and integrate reservoir data management techniques with other reservoir monitoring programs.

GCMRC also plans to continue to work closely with Dr. Richard A. Wildman, currently serving as professor at Quest University Canada and previously a postdoctoral fellow and Harvard University Center for the Environment. GCMRC has provided field assistance, water quality data, and reviews for publications related to phosphorus release and sediment transport related to reservoir drawdown (Wildman and others, 2011; Wildman and Hering, 2011.)

Other potential collaborations include work with Dr. Kevin Speer, Professor of Physical Oceanography at Florida State University. He has proposed using Lake Powell as a testing site for the deployment of unmanned underwater profiling systems. GCMRC has been working with Dr. Kelin Whipple, with the School of Earth and Space Exploration at Arizona State University to share pre-dam topographic files of the Lake Powell basin in conjunction with his research on incision processes in the Colorado River basin. BOR works closely with Brigham Young University on studies of some Utah reservoirs. GCMRC supported a study in August 2013 in which students used various locations in the Colorado River inflow area of Lake Powell for the deployment and refinement of sediment oxygen demand sensors.

D.3 Deliverables

During FY15–17, an interpretive data synthesis report will be published to build on the monitoring data and provide insights into how climatological, meteorological, and hydrodynamic processes, as well as the operation of Glen Canyon Dam, affect inflow routing and stratification in the reservoir and the water quality of releases from Glen Canyon Dam. Each year, the DS-471 report, "Historical Physical and Chemical Data for Water in Lake Powell and from Glen Canyon Dam Releases, Utah-Arizona, 1964–2012", will be revised with final data from the previous year. After initial publication of the biological data report in 2014, these reports will be combined and revised annually. The existing WQDB database will be migrated to the Oracle platform, online access tools and automated statistical and graphical products will be developed, and a website will be developed to provide current conditions and historical data to the public in the form of graphical or statistical summaries. Other reports will be developed in future years describing water-quality changes in response to climatological factors, model development and verification, and application of modeling results to downstream resources.

E. Productivity from Past Work

E.1. Data Products

Products from the Lake Powell monitoring program include published reports, listed in the following section, the WQDB database, which is now available through online download, presentations at scientific meetings, presentations to the general public, and presentations or supporting data to the AMWG and TWG. Preliminary data from monitoring surveys are provided to BOR within one month of collection.

E.2. Completed Publications

Vernieu, W.S., 2013, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964–2012 (ver. 2.0, October 2013): U.S. Geological Survey Data Series 471, 23 p., http://pubs.usgs.gov/ds/471/.

Vernieu, W.S., and Anderson, C.R., 2013, Water temperatures in select nearshore environments of the Colorado River in Grand Canyon, Arizona, during the Low Steady Summer Flow experiment of 2000: U.S. Geological Survey Open-File Report 2013–1066, 44 p., http://pubs.er.usgs.gov/publication/ofr20131066.

Ross, R.P., and Vernieu, W.S., 2013, Nearshore temperature findings for the Colorado River in Grand Canyon, Arizona--Possible implications for native fish: U.S. Geological Survey Fact Sheet 2013-3104, 4 p., http://dx.doi.org/10.3133/fs20133104.

E.3. Publications in progress

Vernieu, W.S., 2014, Biological data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1991-2008: U.S. Geological Survey Data Series xxx (in review).

Vernieu, W.S., 2013, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964–2013 (ver. 3.0): U.S. Geological Survey Data Series 471, 23 p., http://pubs.usgs.gov/ds/471/. (revision for 2013).

E.4. Presentations at professional meetings

11/7/2012 Presentation at North American Lake Management Society 32nd International Symposium titled "Data Management for Long-Term Water-Quality Monitoring in Lake Powell, Utah-Arizona, 1964–2011".

11/8/2012 Presentation at North American Lake Management Society 32nd International Symposium titled "Historic Deltaic Sedimentation Patterns in Lake Powell, Utah-Arizona, 1998-2011".

3/11-13/2013 River Management Society Workshop – presentation cancelled because of sequester.

7/10/2013 Presentation at Museum of Northern Arizona's Science Café lecture series on Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring Program.

9/18/2013 Organized and led special symposium at 12th Biennial Conference of Science and Management on the Colorado Plateau at Northern Arizona University titled "Lake Powell after 50 Years – Patterns, Processes, and Predictions". This session consisted of seven presentations relating to water-quality monitoring, simulation modeling, hydrodynamic processes, quagga mussel status, the Lake Powell sport fishery, contaminant monitoring, and sedimentation patterns.

9/19/2013 Presentation at Arizona Hydrological Society annual symposium in Tucson, AZ titled "Historic Deltaic Sedimentation Patterns in Lake Powell, Utah-Arizona, 1998-2011".

9/20/2013 Interview with Eric Betz, Arizona Daily Sun reporter, for 9/20/2013 article on turbid releases from Glen Canyon Dam in late September (http://azdailysun.com/floods-turn-powell-discharge-murky/article_cfd87d70-2285-11e3-9c56-001a4bcf887a.html).

9/30/2013 Presentations to three middle and high school classes titled "Lake Powell and Glen Canyon Dam – Storing Water in Times of Drought" as part of Flagstaff Festival of Science in-school program.

10/30/2013 Presentation at North American Lake Management Society 33rd International Symposium titled "Biological Data for Water in Lake Powell and from Glen Canyon Dam Releases, Utah-Arizona, 1990–2009".

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G. Budget

Monitoring	Research																	
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total
FY15																	
							1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$183,500**	**$8,700**	**$40,300**	**$0**	**$20,000**	**$20,300**	**$36,900**	**$309,700**
X							1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$183,500	$8,700	$40,300	$0	$0	$20,300	$36,300	$289,100
					X		1.2	Reservoir limnology and ecology monitoring and research science review palen	Vernieu	$0	$0	$0	$0	$20,000	$0	$600	$20,600
FY16																	
							1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$187,200**	**$9,000**	**$41,600**	**$0**	**$0**	**$22,000**	**$50,700**	**$310,500**
X							1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$187,200	$9,000	$41,600	$0	$0	$22,000	$50,700	$310,500
					X		1.2	Reservoir limnology and ecology monitoring and research science review palen	Vernieu	$0	$0	$0	$0	$0	$0	$0	$0
FY17																	
							1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$190,900**	**$9,200**	**$42,800**	**$0**	**$0**	**$23,800**	**$66,500**	**$333,200**
X							1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$190,900	$9,200	$42,800	$0	$0	$23,800	$66,500	$333,200
					X		1.2	Reservoir limnology and ecology monitoring and research science review panel	Vernieu	$0	$0	$0	$0	$0	$0	$0	$0

Appendix 2-A. Fiscal Year 2015 Funding Recommendation

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$20,600**	**$289,100**	**$0**	**$0**	**$0**	**$310,500**	**$0**	**$0**	**$0**	**$333,200**	**$0**
X							1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$0	$289,100	$0	0		$310,500	$0	$0		$333,200	$0
					X		1.2	Reservoir limnology and ecology monitoring and research science review panel	Vernieu	$20,600	$0	$0	$0		$0	$0	$0		$0	$0
X	X						2	**Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem**	Topping et al.	**$1,340,300**	**$0**	**$0**	**$1,452,000**	**$1,350,400**	**$0**	**$0**	**$1,534,900**	**$1,458,200**	**$0**	**$0**

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							3	**Sandbars and Sediment Storage Dynamics**		**$1,324,600**	**$0**	**$0**	**$1,362,800**	**$1,267,400**	**$0**	**$63,100**	**$1,439,600**	**$1,367,600**	**$0**	**$63,300**
X	X						3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$369,100	$0	$0	$354,300		$0	$0	$371,000		$0	$0
X	X						3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$119,700	$0	$0	$130,100		$0	$0	$140,500		$0	$0
		X					3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$42,200	$0	$0	$72,800		$0	$0	$77,300		$0	$0
			X				3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$89,000	$0	$0	$45,100		$0	$45,100	$45,400		$0	$45,300
X	X						3.2	Sediment storage monitoring	Grams et al.	$459,200	$0	$0	$518,000		$0	$0	$546,400		$0	0
			X				3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$100,600	$0	$0	$107,600		$0	$0	$116,200		$0	$0
				X			3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$36,100	$0	$0	$18,100		$0	$18,000	$18,100		$0	$18,000
X	X						3.5	Control network and survey support	Kohl	$108,700	$0	$0	$116,800		$0	$0	$124,700		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	**Support implementation and evaluation of HFE Protocol and Non-Native Fish Control**	**Technical and analytical innovations in monitoring**	**Improving predictive modeling capacity**	**Resolving scientific uncertainty**	**Independent science oversight and review**	**Integrating tribes in monitoring and research**	**Project Identifier**	**Project Description**		**GCDAMP Funded**	**Other BoR Funding**	**Fund Source Not Yet Determined**	**Initial Estimate**	**GCDAMP Funded**	**Other BoR Funding**	**Fund Source Not Yet Determined**	**Initial Estimate**	**GCDAMP Funded**	**Other BoR Funding**	**Fund Source Not Yet Determined**
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$185,600**	**$150,000**	**$0**	**$412,900**	**$384,000**	**$150,000**	**$0**	**$404,700**	**$384,500**	**$186,000**	**$0**
		X					4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$137,300	$75,000	$0	$140,700		$75,000	$0	$159,600		$93,000	$0
X	X						4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$48,300	$75,000	$0	$272,200		$75,000	0	$245,100		$93,000	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							5	**Food Base Monitoring and Research**		**$521,200**	**$0**	**$214,900**	**$591,900**	**$550,500**	**$0**	**$298,900**	**$596,700**	**$566,900**	**$0**	**$459,300**
							5.1	**Are aquatic insect diversity and production recruitment limited?**												
X							5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$117,600	$0	$0	$119,500		$0	$0	$138,200		$0	$0
				X			5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$97,000	$0	$0	$105,000		$0	$0	$117,900		$0	$0
				X			5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$29,600	$0	$0	$32,200		$0	$0	$0		$0	$38,000
				X			5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$29,600	$0	$0	$32,200		$0	$0	$0		$0	$38,000
				X			5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$25,900	$0	$0	$27,600		$0	$0	$0		$0	$31,100
				X			5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$0	$0	$36,900	$0		$0	$40,000	$46,500		$0	$0
				X			5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$0	$0	$58,600	$0		$0	$64,000	$0		$0	$74,700
				X			5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$0	$0	$25,300	$0		$0	$27,300	$0		$0	$31,200
							5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**												
X							5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$51,900	$0	$0	$66,900		$0	$0	$88,400		$0	$0
X							5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$87,100	$0	$0	$115,600		$0	$0	$157,300		$0	$0
				X			5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$20,600	$0	$0	$24,500		$0	$0	$0		$0	$30,000
				X			5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$20,700	$0	$0	$24,600		$0	$0	$30,100		$0	$0
				X			5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$0	$0	$94,100	$0		$0	$167,600	$0		$0	$202,800
							5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**												
X							5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$25,900	$0	$0	$27,100		$0	$0	$0		$0	$13,500
X							5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$15,300	$0	$0	$16,700		$0	$0	$18,300		$0	$0
		X					5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0		$0	$0	$0		$0	$0

Project Elements 5.1.7, 5.1.8, and 5.2.5 (in grey) submitted for non-GCDAMP funding

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
X							6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$567,600**	**$102,700**	**$16,100**	**$626,200**	**$582,400**	**$66,900**	**$15,500**	**$733,800**	**$697,100**	**$0**	**$49,800**
				X			6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$217,700	$0	$0	$241,600		$0	$0	$249,400		$0	$0
		X					6.2	Aggregation recruitment	Dodrill et al.	$0	$84,300	$0	$0		$53,400	$0	$0		$0	$49,800
X							6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$0	$18,400	$0	$0		$13,500	$0	$9,200		$0	$0
		X					6.4	System Wide Electrofishing	Persons and Rogowski	$273,100	$0	$0	$279,700		$0	$0	$316,400		$0	$0
		X		X			6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$16,100	$0		$0	$15,500	$0		$0	$0
X	X						6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$0	$0	$0	$0		$0	$0	$42,900		$0	$0
X	X						6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$76,800	$0	$0	$79,100		$0	$0	$90,100		$0	$0
X							6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$25,800		$0	$0	$25,800		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$1,290,100**	**$261,000**	**$0**	**$1,493,200**	**$1,388,700**	**$215,400**	**$0**	**$1,364,600**	**$1,296,400**	**$0**	**$129,100**
X							7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$530,800	$0	$0	$542,800		$0	$0	$554,500		$0	$0
X							7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$450,700	$0	$0	$468,100		$0	$0	$181,900		$0	$0
				X			7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$0	$111,800	$0	$117,700		$0	$0	$129,500		$0	$0
X							7.4	Remote PIT tag array monitoring in the LCR	Persons	$53,500	$0	$0	$111,100		$0	$0	$152,500		$0	$0
				X			7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$141,100	$0	$0	$87,400		$0	$0	$2,500		$0	$0
				X			7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$0	$11,600	$0	$0		$12,400	$0	$0		$0	$13,800
				X			7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$0	$95,900	$0	$0		$108,000	$0	$64,000		$0	$64,000
X							7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$16,800	$0	$0	$16,700		$0	$0	$18,300		$0	$0
		X					7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$0	$41,700	$0	$0		$95,000	$0	$52,000		$0	$51,300
X			X				7.10	Humpback chub population modelling	Yackulic and Dzul	$97,200	$0	$0	$149,400		$0	$0	$209,400		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$184,500**	**$0**	**$0**	**$226,500**	**$210,600**	**$0**	**$0**	**$296,100**	**$281,300**	**$0**	**$0**
				X			8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$95,900	$0	$0	$118,400		$0	$0	$123,200		$0	$0
X							8.2	Translocation and monitoring above Chute Falls	Persons et al.	$88,600	$0	$0	$87,500		$0	$0	$88,000		$0	$0
					X		8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$20,600		$0	$0	$0		$0	$0
X							8.4	Invasive Species Surveillance and Response	Young et al.	$0	$0	$0	$0		$0	$0	$52,000		$0	$0
				X			8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$0	$0	$0	$0		$0	$0	$32,900		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$924,700**	**$0**	**$137,600**	**$946,200**	**$880,000**	**$0**	**$155,900**	**$602,100**	**$572,000**	**$0**	**$171,900**
X	X			X			9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$180,900	$0	$0	$212,700		$0	$0	$76,900		$0	$0
	X			X			9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$352,500	$0	$0	$436,500		$0	$0	$370,300		$0	$0
				X			9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$102,300	$0	$0	$0		$0	$0	$0		$0	$0
				X			9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$0	$0	$86,100	$0		$0	$103,000	$0		$0	$92,200
				X			9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$20,000	$0	$18,400	$20,000		$0	$18,000	$18,000		$0	$16,600
				X			9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$37,000	$0	$0	$29,000		$0	$0	$0		$0	$29,800
				X			9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$33,200	$0	$33,100	$35,000		$0	$34,900	$33,300		$0	$33,300
				X			9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$72,200	$0	$0	$81,400		$0	$0	$0		$0	$0
	X			X			9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$72,400	$0	$0	$61,800		$0	$0	$98,500		$0	$0
				X			9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$54,200	$0	$0	$69,800		$0	$0	$5,100		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		$8,745,300	$802,800	$368,600	$9,802,800	$9,116,800	$742,800	$670,000	$9,775,500	$9,286,900	$519,200	$922,900
		X		X			10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$148,600**	**$0**	**$0**	**$163,500**	**$152,100**	**$0**	**$0**	**$132,200**	**$125,600**	**$0**	**$0**
							11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$488,100**	**$0**	**$0**	**$551,700**	**$513,100**	**$0**	**$0**	**$504,500**	**$479,300**	**$0**	**$49,500**
X							11.1	Ground-based vegetation monitoring	Ralston et al.	$176,000	$0	$0	$190,900		$0	$0	$211,900		$0	$0
X							11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$154,700	$0	$0	$127,200		$0	$0	$133,100		$0	$0
				X			11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$100,100	$0	$0	$97,800		$0	$0	$49,600		$0	$49,500
				X			11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$23,900	$0	$0	$135,800		$0	$0	$109,900		$0	$0
					X		11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$33,400	$0	$0	$0		$0	$0	$0		$0	$0
							12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$52,000**	**$0**	**$0**	**$86,400**	**$80,400**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
X						X	12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$52,000	$0	$0	$55,500		$0	$0	$0		$0	$0
X						X	12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$30,900		$0	$0	$0		$0	$0

Monitoring		Research								FY15			FY16				FY17			
Core activities	Support implementation and evaluation of HFE Protocol and Non-Native Fish Control	Technical and analytical innovations in monitoring	Improving predictive modeling capacity	Resolving scientific uncertainty	Independent science oversight and review	Integrating tribes in monitoring and research	Project Identifier	Project Description		GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined	Initial Estimate	GCDAMP Funded	Other BoR Funding	Fund Source Not Yet Determined
							3	**Total w/o Lake Powell**		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**
							13	**Socio-economic Monitoring and Research**		**$176,100**	**$0**	**$0**	**$220,300**	**$204,900**	**$0**	**$136,600**	**$356,100**	**$338,300**	**$0**	**$0**
				X			13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$69,600	$0	$0	$73,200		$0	$0	$0		$0	$0
				X			13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$0	$0	$0		$0	$136,600	$128,000		$0	$0
			X				13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$106,500	$0	$0	$147,100		$0	$0	$228,100		$0	$0
X							14	**Geographic Information Systems, Services, and Support**	Gushue et al.	**$222,800**	**$0**	**$0**	**$236,500**	**$219,900**	**$0**	**$0**	**$253,900**	**$241,200**	**$0**	**$0**
							15	**Administration and Support**		**$1,298,500**	**$0**	**$0**	**$1,432,700**	**$1,332,400**	**$0**	**$0**	**$1,556,300**	**$1,478,500**	**$0**	**$0**
X							15.1	GCMRC Admin and Support		$992,900	$0	$0	$1,105,100		$0	$0	$1,205,000		$0	$0
X							15.2	GCMRC logistical support		$305,600	$0	$0	$327,600		$0	$0	$351,300		$0	$0
								Total Lake Powell		$0	$289,100	$0	$0	$0	$310,500	$0	$0	$0	$333,200	$0
								Total AMP		$8,745,300	$513,700	$368,600	$9,802,800	$9,116,800	$432,300	$670,000	$9,775,500	$9,286,900	$186,000	$922,900
								Grand Total		**$8,745,300**	**$802,800**	**$368,600**	**$9,802,800**	**$9,116,800**	**$742,800**	**$670,000**	**$9,775,500**	**$9,286,900**	**$519,200**	**$922,900**

Independent Review
Fisheries Protocol Evaluation Panel (see Project 8.3)
Reservoir Limnology/ecology and linkage PEP (see Project 1.2)
Vegetation Management PEP (see Project 11.5)

Appendix 2-B. Fiscal Year 2015 Budget

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$183,500**	**$8,700**	**$40,300**	**$0**	**$20,000**	**$20,300**	**$36,900**	**$309,700**	**$3,000**	**$6,900**		
1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$183,500	$8,700	$40,300	$0	$0	$20,300	$36,300	$289,100	$0	$6,900	51.1%	WI WSC 51.1%
1.2	Reservoir limnology and ecology monitoring and research science review palen	Vernieu	$0	$0	$0	$0	$20,000	$0	$600	$20,600	$3,000	$0		
2	**Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem**	Topping et al.	**$619,000**	**$5,000**	**$50,000**	**$70,000**	**$0**	**$480,000**	**$116,300**	**$1,340,300**	**$0**	**$193,400**	**67.5%**	AZ WSC 61.85% CIDA 74.625% UT WSC 82.567% WI WSC 51.1%
3	**Sandbars and Sediment Storage Dynamics**		**$549,700**	**$5,900**	**$46,000**	**$56,300**	**$500,600**	**$48,000**	**$118,100**	**$1,324,600**	**$74,500**	**$16,200**		
3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$106,000	$2,000	$4,000	$26,600	$156,100	$48,000	$26,400	$369,100	$23,200	$16,200	51.1%	WI WSC 51.1%
3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$103,500	$0	$0	$0	$0	$0	$16,200	$119,700	$0	$0		
3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$18,700	$0	$0	$0	$20,000	$0	$3,500	$42,200	$3,000	$0		
3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$16,000	$0	$0	$0	$68,400	$0	$4,600	$89,000	$10,200	$0		
3.2	Sediment storage monitoring	Grams et al.	$163,700	$2,000	$27,000	$29,700	$196,100	$0	$40,700	$459,200	$29,200	$0		
3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$64,700	$0	$0	$0	$25,000	$0	$10,900	$100,600	$3,700	$0		
3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100	$5,200	$0		
3.5	Control network and survey support	Kohl	$77,100	$1,900	$15,000	$0	$0	$0	$14,700	$108,700	$0	$0		

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$197,800**	**$9,000**	**$10,000**	**$0**	**$0**	**$84,900**	**$33,900**	**$335,600**	**$0**	**$28,700**		
4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$107,200	$9,000	$2,500	$0	$0	$75,000	$18,600	$212,300	$0	$25,400	51.1%	PCMSC 51.1%
4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$90,600	$0	$7,500	$0	$0	$9,900	$15,300	$123,300	$0	$3,300	51.1%	PCMSC 51.1%

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
5	**Food Base Monitoring and Research**		**$470,900**	**$22,200**	**$37,100**	**$58,000**	**$36,100**	**$18,800**	**$93,000**	**$736,100**	**$5,300**	**$8,800**		
5.1	**Are aquatic insect diversity and production recruitment limited?**		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$80,500	$400	$9,000	$3,800	$9,000	$0	$14,900	$117,600	$1,300	$0		
5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$47,500	$700	$3,000	$26,600	$6,800	$0	$12,400	$97,000	$1,000	$0		
5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$25,200	$400	$0	$0	$0	$0	$4,000	$29,600	$0	$0		
5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$25,200	$400	$0	$0	$0	$0	$4,000	$29,600	$0	$0		
5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$12,600	$700	$3,000	$0	$6,800	$0	$2,800	$25,900	$1,000	$0		
5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$25,200	$700	$6,000	$0	$0	$0	$5,000	$36,900	$0	$0		
5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$39,500	$1,400	$6,000	$3,800	$0	$0	$7,900	$58,600	$0	$0		
5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$12,600	$2,500	$3,000	$3,800	$0	$0	$3,400	$25,300	$0	$0		
5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$36,400	$7,000	$1,500	$0	$0	$0	$7,000	$51,900	$0	$0		
5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$72,800	$1,000	$1,500	$0	$0	$0	$11,800	$87,100	$0	$0		
5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$9,100	$300	$300	$0	$0	$9,400	$1,500	$20,600	$0	$4,400	88.8%	CA WSC 88.8%
5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$9,100	$400	$300	$0	$0	$9,400	$1,500	$20,700	$0	$4,400	88.8%	CA WSC 88.8%
5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$54,600	$5,300	$1,500	$20,000	$0	$0	$12,700	$94,100	$0	$0		
5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,400	$0	$0	$0	$13,500	$0	$2,000	$25,900	$2,000	$0		
5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$10,200	$1,000	$2,000	$0	$0	$0	$2,100	$15,300	$0	$0		
5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$187,000**	**$4,900**	**$29,700**	**$100,300**	**$305,000**	**$0**	**$59,500**	**$686,400**	**$45,400**	**$0**		
6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$55,400	$1,000	$6,100	$36,700	$100,000	$0	$18,500	$217,700	$14,900	$0		
6.2	Aggregation recruitment	Dodrill et al.	$35,400	$0	$6,400	$8,800	$25,000	$0	$8,700	$84,300	$3,700	$0		
6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$8,100	$0	$7,800	$0	$0	$0	$2,500	$18,400	$0	$0		
6.4	System Wide Electrofishing	Persons and Rogowski	$31,900	$0	$8,100	$49,200	$165,000	$0	$18,900	$273,100	$24,600	$0		
6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$600	$0	$15,000	$0	$500	$16,100	$2,200	$0		
6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$56,200	$3,900	$700	$5,600	$0	$0	$10,400	$76,800	$0	$0		
6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$508,600**	**$15,000**	**$61,100**	**$262,300**	**$555,000**	**$0**	**$149,100**	**$1,551,100**	**$82,600**	**$0**		
7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$23,200	$0	$15,500	$90,800	$370,000	$0	$31,300	$530,800	$55,100	$0		
7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$93,600	$0	$8,900	$135,800	$170,000	$0	$42,400	$450,700	$25,300	$0		
7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$62,500	$4,000	$5,400	$24,800	$0	$0	$15,100	$111,800	$0	$0		
7.4	Remote PIT tag array monitoring in the LCR	Persons	$34,700	$0	$3,500	$3,600	$5,000	$0	$6,700	$53,500	$700	$0		
7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$114,800	$2,000	$1,000	$4,200	$0	$0	$19,100	$141,100	$0	$0		
7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,400	$500	$1,000	$3,100	$0	$0	$1,600	$11,600	$0	$0		
7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$53,500	$3,000	$17,500	$0	$10,000	$0	$11,900	$95,900	$1,500	$0		
7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,000	$2,000	$1,500	$0	$0	$0	$2,300	$16,800	$0	$0		
7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$27,900	$1,500	$6,700	$0	$0	$0	$5,600	$41,700	$0	$0		
7.10	Humpback chub population modelling	Yackulic and Dzul	$82,000	$2,000	$100	$0	$0	$0	$13,100	$97,200	$0	$0		

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$53,700**	**$0**	**$7,500**	**$37,600**	**$68,200**	**$0**	**$17,500**	**$184,500**	**$10,200**	**$0**		
8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$49,700	$0	$2,800	$30,400	$0	$0	$13,000	$95,900	$0	$0		
8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,000	$0	$4,700	$7,200	$68,200	$0	$4,500	$88,600	$10,200	$0		
8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
8.4	Invasive Species Surveillance and Response	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$483,200**	**$9,000**	**$94,800**	**$162,400**	**$190,000**	**$0**	**$122,900**	**$1,062,300**	**$28,300**	**$0**		
9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$41,100	$0	$0	$12,900	$115,000	$0	$11,900	$180,900	$17,100	$0		
9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$95,700	$0	$14,900	$127,400	$75,000	$0	$39,500	$352,500	$11,200	$0		
9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$48,500	$0	$40,000	$0	$0	$0	$13,800	$102,300	$0	$0		
9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$72,100	$0	$2,400	$0	$0	$0	$11,600	$86,100	$0	$0		
9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$29,200	$2,500	$1,500	$0	$0	$0	$5,200	$38,400	$0	$0		
9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$27,500	$2,000	$2,500	$0	$0	$0	$5,000	$37,000	$0	$0		
9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$53,800	$2,000	$1,500	$0	$0	$0	$9,000	$66,300	$0	$0		
9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$58,400	$2,500	$1,500	$0	$0	$0	$9,800	$72,200	$0	$0		
9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$12,500	$0	$28,000	$22,100	$0	$0	$9,800	$72,400	$0	$0		
9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$44,400	$0	$2,500	$0	$0	$0	$7,300	$54,200	$0	$0		

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$123,500**	**$5,000**	**$0**	**$0**	**$0**	**$0**	**$20,100**	**$148,600**	**$0**	**$0**		
11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$241,800**	**$8,000**	**$5,500**	**$48,900**	**$126,000**	**$6,700**	**$51,200**	**$488,100**	**$18,700**	**$1,800**		
11.1	Ground-based vegetation monitoring	Ralston et al.	$84,100	$1,500	$1,000	$48,900	$18,800	$0	$21,700	$176,000	$2,800	$0		
11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$41,600	$2,000	$1,500	$0	$99,600	$0	$10,000	$154,700	$14,800	$0		
11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$71,000	$2,000	$1,000	$0	$7,600	$6,700	$11,800	$100,100	$1,100	$1,800	36.4%	FORT 36.4%
11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$16,200	$2,500	$2,000	$0	$0	$0	$3,200	$23,900	$0	$0		
11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$28,900	$0	$0	$0	$0	$0	$4,500	$33,400	$0	$0		
12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$19,600**	**$5,000**	**$2,000**	**$5,000**	**$15,000**	**$0**	**$5,400**	**$52,000**	**$2,200**	**$0**		
12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$19,600	$5,000	$2,000	$5,000	$15,000	$0	$5,400	$52,000	$2,200	$0		
12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		

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	Total w/o Lake Powell		**$4,515,500**	**$140,500**	**$589,100**	**$820,800**	**$1,917,400**	**$638,400**	**$1,005,900**	**$9,627,600**	**$285,400**			
					Burden Rate		15.634%							
13	**Socio-economic Monitoring and Research**		**$118,800**	**$12,500**	**$1,000**	**$0**	**$22,500**	**$0**	**$21,300**	**$176,100**	**$3,400**	**$0**		
13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$54,700	$5,000	$500	$0	$0	$0	$9,400	$69,600	$0	$0		
13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		
13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$64,100	$7,500	$500	$0	$22,500	$0	$11,900	$106,500	$3,400	$0		
14	**Geographic Information Systems, Services, and Support**	Gushue et al.	**$171,300**	**$4,000**	**$17,400**	**$0**	**$0**	**$0**	**$30,100**	**$222,800**	**$0**	**$0**		
15	**Administration and Support**		**$770,600**	**$35,000**	**$227,000**	**$20,000**	**$79,000**	**$0**	**$166,900**	**$1,298,500**	**$11,800**	**$0**		
15.1	GCMRC Admin and Support		$511,300	$30,000	$227,000	$20,000	$79,000	$0	$125,600	$992,900	$11,800	$0		
15.2	GCMRC logistical support		$259,300	$5,000	$0	$0	$0	$0	$41,300	$305,600	$0	$0		
	Total Lake Powell		$183,500	$8,700	$40,300	$0	$0	$20,300	$36,300	$289,100	$0	$6,900		
	Total AMP		$4,515,500	$140,500	$589,100	$820,800	$1,917,400	$638,400	$1,005,900	$9,627,600	$285,400	$248,900		
	Grand Total		**$4,699,000**	**$149,200**	**$629,400**	**$820,800**	**$1,917,400**	**$658,700**	**$1,042,200**	**$9,916,700**	**$285,400**	**$255,800**		

Independent Review
Fisheries Protocol Evaluation Panel (see Project 8.3)
Reservoir Limnology/ecology and linkage PEP (see Project 1.2)
Vegetation Management PEP (see Project 11.5)

Appendix 2-C. Fiscal Year 2016 Budget

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$187,200**	**$9,000**	**$41,600**	**$0**	**$0**	**$22,000**	**$50,700**	**$310,500**	**$0**	**$7,400**	
1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$187,200	$9,000	$41,600	$0	$0	$22,000	$50,700	$310,500	$0	$7,400	
1.2	Reservoir limnology and ecology monitoring and research science review palen	Vernieu	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
2	**Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem**	Topping et al.	**$659,000**	**$5,000**	**$52,000**	**$72,000**	**$0**	**$496,000**	**$168,000**	**$1,452,000**	**$0**	**$199,900**	
3	**Sandbars and Sediment Storage Dynamics**		**$589,500**	**$5,900**	**$46,000**	**$92,400**	**$500,600**	**$20,000**	**$171,500**	**$1,425,900**	**$74,500**	**$6,800**	
3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$109,100	$2,000	$4,000	$27,900	$156,100	$20,000	$35,200	$354,300	$23,200	$6,800	
3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$107,200	$0	$0	$0	$0	$0	$22,900	$130,100	$0	$0	
3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$43,000	$0	$0	$0	$20,000	$0	$9,800	$72,800	$3,000	$0	
3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$16,300	$0	$0	$0	$68,400	$0	$5,500	$90,200	$10,200	$0	
3.2	Sediment storage monitoring	Grams et al.	$167,000	$2,000	$27,000	$64,500	$196,100	$0	$61,400	$518,000	$29,200	$0	
3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$67,500	$0	$0	$0	$25,000	$0	$15,100	$107,600	$3,700	$0	
3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100	$5,200	$0	
3.5	Control network and survey support	Kohl	$79,400	$1,900	$15,000	$0	$0	$0	$20,500	$116,800	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$285,000**	**$14,000**	**$63,000**	**$30,000**	**$0**	**$87,300**	**$83,600**	**$562,900**	**$0**	**$29,500**	
4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$99,200	$10,000	$5,000	$0	$0	$77,100	$24,400	$215,700	$0	$26,100	
4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$185,800	$4,000	$58,000	$30,000	$0	$10,200	$59,200	$347,200	$0	$3,400	

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					Burden Rate		21.325%						
5	**Food Base Monitoring and Research**		**$530,900**	**$22,600**	**$38,200**	**$59,800**	**$78,500**	**$19,400**	**$141,400**	**$890,800**	**$11,700**	**$9,200**	
5.1	**Are aquatic insect diversity and production recruitment limited?**												
5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$83,300	$400	$9,300	$3,900	$1,900	$0	$20,700	$119,500	$300	$0	
5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$49,300	$700	$3,100	$27,500	$7,000	$0	$17,400	$105,000	$1,000	$0	
5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$26,100	$400	$0	$0	$0	$0	$5,700	$32,200	$0	$0	
5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$26,100	$400	$0	$0	$0	$0	$5,700	$32,200	$0	$0	
5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$13,000	$700	$3,100	$0	$7,000	$0	$3,800	$27,600	$1,000	$0	
5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$26,100	$700	$6,200	$0	$0	$0	$7,000	$40,000	$0	$0	
5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$40,800	$1,400	$6,200	$3,900	$500	$0	$11,200	$64,000	$100	$0	
5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$13,000	$2,500	$3,100	$3,900	$0	$0	$4,800	$27,300	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**												
5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$46,400	$7,200	$1,500	$0	$0	$0	$11,800	$66,900	$0	$0	
5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$92,800	$1,000	$1,500	$0	$0	$0	$20,300	$115,600	$0	$0	
5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$11,600	$300	$300	$0	$0	$9,700	$2,600	$24,500	$0	$4,600	
5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$11,600	$400	$300	$0	$0	$9,700	$2,600	$24,600	$0	$4,600	
5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$69,600	$5,500	$1,500	$20,600	$48,200	$0	$22,200	$167,600	$7,200	$0	
5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**												
5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,500	$0	$0	$0	$13,900	$0	$2,700	$27,100	$2,100	$0	
5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$10,700	$1,000	$2,100	$0	$0	$0	$2,900	$16,700	$0	$0	
5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$180,100**	**$5,700**	**$21,200**	**$118,000**	**$305,000**	**$0**	**$78,600**	**$708,600**	**$45,400**	**$0**	
6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$62,500	$1,200	$6,200	$44,300	$100,000	$0	$27,400	$241,600	$14,900	$0	
6.2	Aggregation recruitment	Dodrill et al.	$31,000	$500	$3,500	$9,000	$0	$0	$9,400	$53,400	$0	$0	
6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$8,400	$0	$2,700	$0	$0	$0	$2,400	$13,500	$0	$0	
6.4	System Wide Electrofishing	Persons and Rogowski	$22,700	$0	$8,100	$59,700	$165,000	$0	$24,200	$279,700	$24,600	$0	
6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$0	$0	$15,000	$0	$500	$15,500	$2,200	$0	
6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$55,500	$4,000	$700	$5,000	$0	$0	$13,900	$79,100	$0	$0	
6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$25,000	$0	$800	$25,800	$3,700	$0	

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$603,400**	**$13,300**	**$52,400**	**$267,900**	**$555,000**	**$0**	**$216,600**	**$1,708,600**	**$82,600**	**$0**	
7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$26,900	$0	$8,300	$98,100	$370,000	$0	$39,500	$542,800	$55,100	$0	
7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$96,700	$0	$9,000	$135,800	$170,000	$0	$56,600	$468,100	$25,300	$0	
7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$60,900	$4,000	$5,300	$26,800	$0	$0	$20,700	$117,700	$0	$0	
7.4	Remote PIT tag array monitoring in the LCR	Persons	$79,900	$0	$3,500	$3,900	$5,000	$0	$18,800	$111,100	$700	$0	
7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$70,000	$2,000	$0	$0	$0	$0	$15,400	$87,400	$0	$0	
7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,600	$300	$1,000	$3,300	$0	$0	$2,200	$12,400	$0	$0	
7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$59,500	$3,000	$18,000	$0	$10,000	$0	$17,500	$108,000	$1,500	$0	
7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,300	$2,000	$500	$0	$0	$0	$2,900	$16,700	$0	$0	
7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$71,600	$0	$6,700	$0	$0	$0	$16,700	$95,000	$0	$0	
7.10	Humpback chub population modelling	Yackulic and Dzul	$121,000	$2,000	$100	$0	$0	$0	$26,300	$149,400	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$61,400**	**$0**	**$5,100**	**$45,300**	**$88,200**	**$0**	**$26,500**	**$226,500**	**$13,200**	**$0**	
8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$57,300	$0	$2,800	$37,500	$0	$0	$20,800	$118,400	$0	$0	
8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,100	$0	$2,300	$7,800	$68,200	$0	$5,100	$87,500	$10,200	$0	
8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$20,000	$0	$600	$20,600	$3,000	$0	
8.4	Invasive Species Surveillance and Response	Young et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$483,600**	**$7,500**	**$87,500**	**$168,400**	**$190,000**	**$0**	**$165,100**	**$1,102,100**	**$28,300**	**$0**	
9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$62,300	$2,500	$0	$12,900	$115,000	$0	$20,000	$212,700	$17,100	$0	
9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$100,500	$0	$50,100	$145,500	$75,000	$0	$65,400	$436,500	$11,200	$0	
9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$80,000	$2,500	$2,400	$0	$0	$0	$18,100	$103,000	$0	$0	
9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$29,800	$0	$1,500	$0	$0	$0	$6,700	$38,000	$0	$0	
9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$21,400	$0	$2,500	$0	$0	$0	$5,100	$29,000	$0	$0	
9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$56,100	$0	$1,500	$0	$0	$0	$12,300	$69,900	$0	$0	
9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$65,600	$0	$1,500	$0	$0	$0	$14,300	$81,400	$0	$0	
9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$12,900	$0	$28,000	$10,000	$0	$0	$10,900	$61,800	$0	$0	
9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$55,000	$2,500	$0	$0	$0	$0	$12,300	$69,800	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$129,800**	**$5,000**	**$0**	**$0**	**$0**	**$0**	**$28,700**	**$163,500**	**$0**	**$0**	
11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$244,300**	**$13,500**	**$7,500**	**$65,400**	**$139,500**	**$6,800**	**$74,700**	**$551,700**	**$20,700**	**$1,800**	
11.1	Ground-based vegetation monitoring	Ralston et al.	$88,700	$1,000	$1,000	$50,400	$19,100	$0	$30,700	$190,900	$2,800	$0	
11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$44,900	$2,000	$2,000	$0	$65,900	$0	$12,400	$127,200	$9,800	$0	
11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$63,500	$2,500	$2,500	$0	$7,700	$6,800	$14,800	$97,800	$1,100	$1,800	
11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$47,200	$8,000	$2,000	$15,000	$46,800	$0	$16,800	$135,800	$7,000	$0	
11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$20,000**	**$2,500**	**$5,500**	**$5,000**	**$45,000**	**$0**	**$8,400**	**$86,400**	**$6,700**	**$0**	
12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$20,000	$2,500	$5,500	$5,000	$15,000	$0	$7,500	$55,500	$2,200	$0	
12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$30,000	$0	$900	$30,900	$4,500	$0	
13	**Socio-economic Monitoring and Research**		**$124,900**	**$12,500**	**$11,100**	**$0**	**$171,500**	**$0**	**$36,900**	**$356,900**	**$25,500**	**$0**	
13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$57,500	$2,500	$300	$0	$0	$0	$12,900	$73,200	$0	$0	
13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$2,500	$10,300	$0	$117,500	$0	$6,300	$136,600	$17,500	$0	
13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$67,400	$7,500	$500	$0	$54,000	$0	$17,700	$147,100	$8,000	$0	

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	Total w/o Lake Powell		**$4,912,500**	**$151,000**	**$632,000**	**$944,200**	**$2,154,800**	**$629,500**	**$1,481,100**	**$10,905,100**	**$320,700**	**$247,200**	
					Burden Rate		21.325%						
14	**Geographic Information Systems, Services, and Support**	Gushue et al.	**$172,900**	**$6,000**	**$16,000**	**$0**	**$0**	**$0**	**$41,600**	**$236,500**	**$0**	**$0**	
15	**Administration and Support**		**$827,700**	**$37,500**	**$226,500**	**$20,000**	**$81,500**	**$0**	**$239,500**	**$1,432,700**	**$12,100**	**$0**	
15.1	GCMRC Admin and Support		$563,200	$32,000	$226,500	$20,000	$81,500	$0	$181,900	$1,105,100	$12,100	$0	
15.2	GCMRC logistical support		$264,500	$5,500	$0	$0	$0	$0	$57,600	$327,600	$0	$0	
	Total Lake Powell		$187,200	$9,000	$41,600	$0	$0	$22,000	$50,700	$310,500	$0	$7,400	
	Total AMP		$4,912,500	$151,000	$632,000	$944,200	$2,154,800	$629,500	$1,481,100	$10,905,100	$320,700	$247,200	
	Grand Total		**$5,099,700**	**$160,000**	**$673,600**	**$944,200**	**$2,154,800**	**$651,500**	**$1,531,800**	**$11,215,600**	**$320,700**	**$254,600**	

Independent Review
Fisheries Protocol Evaluation Panel (see Project 8.3)
Reservoir Limnology/ecology and linkage PEP (see Project 1.2)
Vegetation Management PEP (see Project 11.5)

Appendix 2-D. Fiscal Year 2017 Budget

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
1	**Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring**		**$190,900**	**$9,200**	**$42,800**	**$0**	**$0**	**$23,800**	**$66,500**	**$333,200**	**$0**	**$8,000**	
1	Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring	Vernieu	$190,900	$9,200	$42,800	$0	$0	$23,800	$66,500	$333,200	$0	$8,000	
1.2	Reservoir limnology and ecology monitoring and research science review panel	Vernieu	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
2	**Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem**	Topping et al.	**$671,000**	**$5,000**	**$53,000**	**$74,000**	**$0**	**$512,000**	**$219,900**	**$1,534,900**	**$0**	**$206,300**	
3	**Sandbars and Sediment Storage Dynamics**		**$611,600**	**$5,900**	**$46,000**	**$95,800**	**$500,600**	**$20,000**	**$223,000**	**$1,502,900**	**$74,500**	**$6,800**	
3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$114,200	$2,000	$4,000	$29,100	$156,100	$20,000	$45,600	$371,000	$23,200	$6,800	
3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$110,300	$0	$0	$0	$0	$0	$30,200	$140,500	$0	$0	
3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$44,500	$0	$0	$0	$20,000	$0	$12,800	$77,300	$3,000	$0	
3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$15,900	$0	$0	$0	$68,400	$0	$6,400	$90,700	$10,200	$0	
3.2	Sediment storage monitoring	Grams et al.	$174,700	$2,000	$27,000	$66,700	$196,100	$0	$79,900	$546,400	$29,200	$0	
3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$71,000	$0	$0	$0	$25,000	$0	$20,200	$116,200	$3,700	$0	
3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$0	$0	$0	$0	$35,000	$0	$1,100	$36,100	$5,200	$0	
3.5	Control network and survey support	Kohl	$81,000	$1,900	$15,000	$0	$0	$0	$26,800	$124,700	$0	$0	

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	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
4	**Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability**		**$317,200**	**$14,000**	**$34,000**	**$30,000**	**$0**	**$87,300**	**$108,200**	**$590,700**	**$0**	**$29,500**	
4.1	Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales	Sankey et al.	$119,800	$10,000	$8,000	$0	$0	$77,100	$37,700	$252,600	$0	$26,100	
4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$197,400	$4,000	$26,000	$30,000	$0	$10,200	$70,500	$338,100	$0	$3,400	

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	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
5	**Food Base Monitoring and Research**												
5.1	**Are aquatic insect diversity and production recruitment limited?**		**$635,300**	**$23,300**	**$39,400**	**$61,500**	**$66,500**	**$20,000**	**$210,000**	**$1,056,000**	**$9,900**	**$9,400**	
5.1.1	Insect emergence in Grand Canyon via citizen science	Kennedy and Yackulic	$93,500	$400	$9,500	$4,000	$1,400	$0	$29,400	$138,200	$200	$0	
5.1.2	Quantifying the effects of hydropeaking on oviposition and egg mortality	Kennedy and Muehlbauer	$54,500	$700	$3,200	$28,300	$7,200	$0	$24,000	$117,900	$1,100	$0	
5.1.3	Synthesis of stressors and controls on EPT distributions	Muehlbauer et al.	$29,400	$400	$0	$0	$0	$0	$8,200	$38,000	$0	$0	
5.1.4	Synthesis of the aquatic foodbase in western US tailwaters	Muehlbauer et al.	$29,400	$400	$0	$0	$0	$0	$8,200	$38,000	$0	$0	
5.1.5	Natural history of oviposition for species present in Grand Canyon	Kennedy et al.	$14,700	$700	$3,200	$0	$7,200	$0	$5,300	$31,100	$1,100	$0	
5.1.6	Laboratory studies on insect oviposition and egg mortality associated with changing water levels	Kennedy and Copp	$29,400	$700	$6,400	$0	$0	$0	$10,000	$46,500	$0	$0	
5.1.7	Comparative emergence studies in Upper Basin using citizen science light trapping	Kennedy et al.	$45,900	$1,500	$6,400	$4,000	$1,000	$0	$15,900	$74,700	$100	$0	
5.1.8	Natural history of oviposition for EPT via studies in the Upper Basin	Kennedy et al.	$14,700	$2,600	$3,200	$4,000	$0	$0	$6,700	$31,200	$0	$0	
5.2	**Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters**												
5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$60,400	$7,400	$1,600	$0	$0	$0	$19,000	$88,400	$0	$0	
5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$120,800	$1,100	$1,600	$0	$0	$0	$33,800	$157,300	$0	$0	
5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer & Wright	$15,100	$300	$300	$0	$0	$10,000	$4,300	$30,000	$0	$4,700	
5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer & Wright	$15,100	$400	$300	$0	$0	$10,000	$4,300	$30,100	$0	$4,700	
5.2.5	Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters	Kennedy et al.	$90,600	$5,600	$1,600	$21,200	$49,700	$0	$34,100	$202,800	$7,400	$0	
5.3	**Primary Production Monitoring in Glen Marble and Grand Canyons**												
5.3.1	Synthesis and publication of Glen Canyon algae production	Kennedy, Yackulic, Yard, Payn & Hall	$10,600	$0	$0	$0	$0	$0	$2,900	$13,500	$0	$0	
5.3.2	Monitoring dissolved oxygen in Glen, Marble, and Grand Canyon	Copp & Voichick	$11,200	$1,100	$2,100	$0	$0	$0	$3,900	$18,300	$0	$0	
5.3.3	Developing automated tools for estimating algae production	Yackulic, Hall & Stets	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	

Project Identifier	Project Description		Salaries	Travel & Training	Operating Expenses	Logistics	Coop-erators (non-USGS)	USGS Coop-erators	USGS/SBSC Burden	Total	Coop-erators (non-USGS) Estimated Burden	USGS Coop-erators Estimated Burden	Notes
	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
6	**Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics**		**$189,800**	**$5,700**	**$26,300**	**$118,300**	**$340,000**	**$0**	**$103,500**	**$783,600**	**$50,700**	**$0**	
6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$63,300	$1,200	$6,200	$44,200	$100,000	$0	$34,500	$249,400	$14,900	$0	
6.2	Aggregation recruitment	Dodrill et al.	$26,000	$500	$3,500	$9,100	$0	$0	$10,700	$49,800	$0	$0	
6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$4,400	$0	$2,800	$0	$0	$0	$2,000	$9,200	$0	$0	
6.4	System Wide Electrofishing	Persons and Rogowski	$30,700	$0	$8,100	$60,000	$185,000	$0	$32,600	$316,400	$27,600	$0	
6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
6.6	Direct Mainstem Augmentation of Humpback Chub	Young et al.	$4,400	$0	$5,000	$0	$30,000	$0	$3,500	$42,900	$4,500	$0	
6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$61,000	$4,000	$700	$5,000	$0	$0	$19,400	$90,100	$0	$0	
6.8	Lees Ferry Creel Survey	Rogowski and Persons	$0	$0	$0	$0	$25,000	$0	$800	$25,800	$3,700	$0	
7	**Population Ecology of Humpback Chub in and around the Little Colorado River**		**$587,000**	**$13,300**	**$52,500**	**$168,200**	**$435,000**	**$0**	**$237,700**	**$1,493,700**	**$64,700**	**$0**	
7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$22,400	$0	$8,400	$105,300	$370,000	$0	$48,400	$554,500	$55,100	$0	
7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$67,100	$0	$9,000	$26,300	$50,000	$0	$29,500	$181,900	$7,400	$0	
7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$63,600	$4,000	$5,300	$28,800	$0	$0	$27,800	$129,500	$0	$0	
7.4	Remote PIT tag array monitoring in the LCR	Persons	$108,000	$0	$3,500	$4,200	$5,000	$0	$31,800	$152,500	$700	$0	
7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$0	$2,000	$0	$0	$0	$0	$500	$2,500	$0	$0	
7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$5,900	$300	$1,000	$3,600	$0	$0	$3,000	$13,800	$0	$0	
7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$71,400	$3,000	$18,000	$0	$10,000	$0	$25,600	$128,000	$1,500	$0	
7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$11,900	$2,000	$500	$0	$0	$0	$3,900	$18,300	$0	$0	
7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$74,400	$0	$6,700	$0	$0	$0	$22,200	$103,300	$0	$0	
7.10	Humpback chub population modelling	Yackulic and Dzul	$162,300	$2,000	$100	$0	$0	$0	$45,000	$209,400	$0	$0	

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					Burden Rate		27.380%						
8	**Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon**		**$69,400**	**$0**	**$6,300**	**$44,900**	**$138,200**	**$0**	**$37,300**	**$296,100**	**$20,600**	**$0**	
8.1	Efficacy and ecological impacts of Trout removal	Ward and Healy	$56,200	$0	$2,800	$37,700	$0	$0	$26,500	$123,200	$0	$0	
8.2	Translocation and monitoring above Chute Falls	Persons et al.	$4,400	$0	$2,300	$7,200	$68,200	$0	$5,900	$88,000	$10,200	$0	
8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
8.4	Invasive Species Surveillance and Response	Young et al.	$4,400	$0	$0	$0	$45,000	$0	$2,600	$52,000	$6,700	$0	
8.5	Genetic Monitoring of Lower Basin Humpback Chub	Wilson et al.	$4,400	$0	$1,200	$0	$25,000	$0	$2,300	$32,900	$3,700	$0	
9	**Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**		**$357,600**	**$0**	**$86,000**	**$123,700**	**$50,000**	**$0**	**$156,700**	**$774,000**	**$7,400**	**$0**	
9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$60,400	$0	$0	$0	$0	$0	$16,500	$76,900	$0	$0	
9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$98,600	$0	$50,100	$101,600	$50,000	$0	$70,000	$370,300	$7,400	$0	
9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$70,000	$0	$2,400	$0	$0	$0	$19,800	$92,200	$0	$0	
9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$25,700	$0	$1,500	$0	$0	$0	$7,400	$34,600	$0	$0	
9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$20,900	$0	$2,500	$0	$0	$0	$6,400	$29,800	$0	$0	
9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$50,800	$0	$1,500	$0	$0	$0	$14,300	$66,600	$0	$0	
9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$27,200	$0	$28,000	$22,100	$0	$0	$21,200	$98,500	$0	$0	
9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$4,000	$0	$0	$0	$0	$0	$1,100	$5,100	$0	$0	

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	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
			$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
10	**Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam**	Melis et al.	**$96,800**	**$7,000**	**$0**	**$0**	**$0**	**$0**	**$28,400**	**$132,200**	**$0**	**$0**	
11	**Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis**		**$247,600**	**$9,300**	**$8,000**	**$60,000**	**$129,400**	**$6,900**	**$92,800**	**$554,000**	**$19,300**	**$1,800**	
11.1	Ground-based vegetation monitoring	Ralston et al.	$96,400	$1,200	$1,000	$52,000	$19,500	$0	$41,800	$211,900	$2,900	$0	
11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$46,700	$1,500	$2,000	$0	$67,100	$0	$15,800	$133,100	$10,000	$0	
11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$61,000	$2,600	$2,500	$0	$7,800	$6,900	$18,300	$99,100	$1,200	$1,800	
11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$43,500	$4,000	$2,500	$8,000	$35,000	$0	$16,900	$109,900	$5,200	$0	
11.5	Science Review Panel of Successes and Challenges in Non-native Vegetation Control in the Colorado River and Rio Grande Watersheds	Sarr et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	
12.1	Tribal workshop and analysis of cultural landscape change	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
12.2	Tribal evaluations of cultural landscape changes	Fairley et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
13	**Socio-economic Monitoring and Research**		**$127,400**	**$12,500**	**$1,000**	**$0**	**$171,500**	**$0**	**$43,700**	**$356,100**	**$25,500**	**$0**	
13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	
13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam	Bair et al.	$0	$5,000	$500	$0	$117,500	$0	$5,000	$128,000	$17,500	$0	
13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$127,400	$7,500	$500	$0	$54,000	$0	$38,700	$228,100	$8,000	$0	

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	Total w/o Lake Powell		**$4,937,900**	**$140,000**	**$614,500**	**$796,400**	**$1,915,200**	**$646,200**	**$1,834,200**	**$10,884,400**	**$285,100**	**$253,800**	
					Burden Rate		27.380%						
14	**Geographic Information Systems, Services, and Support**	Gushue et al.	**$179,300**	**$4,000**	**$16,000**	**$0**	**$0**	**$0**	**$54,600**	**$253,900**	**$0**	**$0**	
15	**Administration and Support**		**$847,900**	**$40,000**	**$246,000**	**$20,000**	**$84,000**	**$0**	**$318,400**	**$1,556,300**	**$12,500**	**$0**	
15.1	GCMRC Admin and Support		$578,100	$34,000	$246,000	$20,000	$84,000	$0	$242,900	$1,205,000	$12,500	$0	
15.2	GCMRC logistical support		$269,800	$6,000	$0	$0	$0	$0	$75,500	$351,300	$0	$0	
	Total Lake Powell		$190,900	$9,200	$42,800	$0	$0	$23,800	$66,500	$333,200	$0	$8,000	
	Total AMP		$4,937,900	$140,000	$614,500	$796,400	$1,915,200	$646,200	$1,834,200	$10,884,400	$285,100	$253,800	
	Grand Total		**$5,128,800**	**$149,200**	**$657,300**	**$796,400**	**$1,915,200**	**$670,000**	**$1,900,700**	**$11,217,600**	**$285,100**	**$261,800**	

Independent Review
Fisheries Protocol Evaluation Panel (see Project 8.3)
Reservoir Limnology/ecology and linkage PEP (see Project 1.2)
Vegetation Management PEP (see Project 11.5)

Appendix 3. Logistics and Schedules of River Trips and Field Work

	PROJECT TITLE	PROJECT CODE	GENERAL LOGISTICS DESCRIPTION	LOGISTICS TYPE (RT=river trip, LP=Lake Powell, HS=Helicopter Support, LF=Glen Canyon Reach	annual # trips	trip months	boats	#people	#days
1	**Lake Powell and Glen Canyon Dam Release Water Quality Monitoring**								
		LPQM	food packs provided for quarterly Lake Powell monitorng trips, 4-6 people, 7 days, includes limited boat/motor maintence support	LP	4				
2	**Stream flow, water quality, and sediment transport**								
		FGS	two river trips anually, to monitor sediment transport at monitoring stations; 30 mi., 60 mi., Phantom, National and Diamond Creek	RT	2	February, late August	2 support, 1-16' technical		
3	**Sandbars and Sediment Storage Dynamics**								
3.1	Sandbar and camping beach monitoring	FCS	one river trip anually to survey established longterm set of monitoring sites. Non motorized trip consisting of 6-18' row boats occurs in October	RT	1	October	6 row	12	18
3.2	Sediment storage monitoring	SSM	one river trip anually, motor supported trip occurs April/May to map channel in rotating reaches of river. In 2015, mapping will occur in Glen Canyon reach which will require less equipment and personnel. The project plans to survey RM 0-RM30 in 2016 and RM 166-RM225 in 2017.	RT	1	May	2 support, 2-22' technical (multi-beam and "eye-ball"), 1-16' technical (single beam), 1-16' technical	20	19
4	**Connectivity along the fluvial-aeolian hillslope continuum**								
4.1	Monitoring the status of cultural resources in Glen Canyon			LF	1	Nov/Dec	cofelt	2	4
4.2	. Monitoring strategies for the status of cultural resources in Grand Canyon		one river trip to monitor designated sites and maintain weather stations, additional logistics for weater station maintenace will be covered on existing scheduled trips (GCY, FCS, NO/JCM). In 2015 monitoring will only occur in Glen Canyon reach. 2016 and 2017	RT	1	May	1-support, 1-22'	10	13

	PROJECT TITLE	PROJECT CODE	GENERAL LOGISTICS DESCRIPTION	LOGISTICS TYPE (RT=river trip, LP=Lake Powell, HS=Helicopter Support, LF=Glen Canyon Reach	annual # trips	trip months	boats	#people	#days
5	**Foodbase Monitoring and Research**								
5.1	AQFB Emergence Trip	**AQFB**	one river trip annually, citizen science	RT	1	June	1-support, 1-22', 1-sport boat	5	15
5.2	AQFB Invertebrate Drift: Dam to Badger Rapids	**AQFB-LF**	monthly trips, Copp or Smith will operate boat (no boatman needed).	LF (to Badger)	12	Monthly	coffelt or jet boat	3	2
	AQFB Invertebrate Drift: upper/lower basin	AQFB-U/LB	one trip annually to upper and lower basin (separate trips)	Logistics are similar to LF, except not in LF	2	June-August? TBA	1-sport boat, or coffelt	3	8
	AQFB Invertebrate Drift: mainstem	AQFB-NO	work is conducted on NO/JCM trips	RT					
6	**Mainstem humpback chub aggregations and fish community dynamics**								
6.1	Monitoring Humpback Chub aggregation relative Abundance and Distribution	MSF-AG	one river trips anually, to support monitoring focused on identified HBC aggregations	RT	1	July, September	2-support, 2-16' technical	10	18
6.2	Humpback Chub aggregation recruitment studies		work is conducted on project 6.1 logistics with addition of one sport boat for electroshocking/seining				1-16' technical boat		
6.3	Mainstem. PIT tag antenna monitoring		maintence of remote PIT tag array as needed	HS	(will tag on to existing trips)			2	
6.4	System wide electrofishing	MSF-NN	two river trips anually, to electrofish sample entire river corridor,	RT	2	April, May	2-support, 2-16' technical	10	14
6.5	Brown Trout natal origins		no stand alone logistics-work will be conducted on existing logistics						
6.6	Mainstem Translocation		no stand alone logistics-work will be conducted on existing logistics						
6.7	Rainbow trout early life stage studies	Redd/RTELSS	8 winter/spring one day trips to survey Glen Canyon reach for RBT redds, and 4 sampling trips utilizing electrofishing and backpack shocking to monitor RBT early life stage	LF	8 Redd, 4 RTLESS	Redd: Dec, Jan, Feb, March, April RTELSS: July, Aug, Sept, Nov	Cofelt, 2-16' technical	2	Redd: one day trips, RTELSS: 2-16' technic al
6.8	LF Creel Survey		work conducted by AZGFD-no logistics						

	PROJECT TITLE	PROJECT CODE	GENERAL LOGISTICS DESCRIPTION	LOGISTICS TYPE (RT=river trip, LP=Lake Powell, HS=Helicopter Support, LF=Glen Canyon Reach	annual # trips	trip months	boats	#people	#days
7	**Population Ecology of Humpback Chub in and around the Little Colorado River**								
7.1	Annual spring and fall humpback chub abundance estimates in the downstream 13.6km of the Little Colorado River	LCR-HBC	helicopter support for 3 LCR camps, April/May and September/October, 9 people, 11 days per trip	HS	4	April, May, September, October		9	11
7.2	Juvenile Chub Monitoring in the mainstem near the Little Colorado River Confluence	JCM	Logistics are combined with project 9.2 (days 7-16 of river trip) to sample for HBC near LCR confluence.	RT	4	May, July, September, January* (January trip may be eliminated)	2-support, 1-22' Processing boat 3-16' technical	18	18
7.3	LCR JCM		helicopter support for 3 LCR camps to monitor LCR HBC populations	HS	1	June/July		12	12
7.4	LCR PIT tag antenna monitoring		maintence of remote PIT tag array as needed	HS	1			2	4
7.5	LCR foodweb		work is conducted in conjunction with project 7.1 trips	HS					
8	**Management Actions to Increase Abundancee and Distribution of Native Fishes in Grand Canyon**								
8.1	Efficacy and ecological impacts of brown trout removal at Bright Angel Creek		new project to colaborate with NPS to remove Brown trout in Bright Angel Creek confluence. Logistics could be coupled with F.3/F.6 project run-out.	RT	2	May, September	1-support, 2-16' technical	8	18
8.2	F.4.3. Translocation and monitoring above Chute Falls		3 helicopter supported trips for HBC mark/recap and translocation/capture	HS	3	April/May, July			
8.3	**PEP**		may be one river trip for PEP in 2016	RT	1	?	2-support	18	12

	PROJECT TITLE	PROJECT CODE	GENERAL LOGISTICS DESCRIPTION	LOGISTICS TYPE (RT=river trip, LP=Lake Powell, HS=Helicopter Support, LF=Glen Canyon Reach	annual # trips	trip months	boats	#people	#days
9	**Understanding the Factors Limiting the Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons**								
9.1	Glen Canyon Rainbow trout; monitoring, analysis and study design	LFT	3 Glen Canyon trips to monitor RBT population, includes additional day on July trip for non-native fish detection	LF	3	April, July, October	2-16' technical	4	4days, July trip 5 days
9.2	Detection of rainbow trout movement from Glen Canyon to Marble Canyon	NO	Logistics are combined with project 7.2 (first six days of river trip) to electrofish sample for tagged RBT between Glen Canyon Dam and LCR confluence.	RT	4	May, July, September, January* (January trip may be eliminated)	2-support, 1-22' Processing boat 3-16' technical	18	18
9.3	Detection of rainbow trout movement from Glen Canyon to Marble Canyon-Lees Ferry marking	NO-mark	november Glen Canyon marking trip	Glen Canyon	1	November	1-support, 1-22' processing boat, 2-16' technical, cofelt	10	9
9.9	Contingency planning for High Flow Experiments and subsequent rainbow trout population managment		1 additional RBT marking trip in Glen Canyon post HFE (in years when fall HFE occurs)	Glen Canyon	1	Dec	1-support, 1-22' processing boat, 2-16' technical, cofelt	10	9
10	**Mapping Flow Innundation of Shorline Areas and Bed Textures in Glen and Marble Canyons**								
			This project hast no stand-alone logistics but does propose a field element to be accomplished on APR & SEP 2015-16 NO/JCM trips (collecting additional channel-bed sediment and channel margin imagery, See Table 1 of revised description). Other new field data used in this integrated project will derive from Project 3 channel mapping in Glen (2015) and upper/lower Marble Canyons (2015-16, see Grams and others elements 3.2 & 3.4).	RT					
11	**Riparian Vegetation Monitoring and Analysis of Riparian Vegetation, Landform Change and Aquatic-Terrestrial linkages to Faunal Communities**								
	Integrated vegetation monitoring		one river trip to monitor riparian vegetation, plus addition of one boat to project 3.1	RT	1	September	4 row	14	16
12	**Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem**								
			add one boat to project 3.1?	RT		October	1 row	2	16
13	**Socio-Economic Monitoring and Research**								
	LF to Badger creel survey		no additional logistics, surveys completed by foot trail access						

Appendix 4. TWG Triennial Budget Input FY 2015–17 Consensus by full TWG on April 9, 2014

April 10, 2014

HUMPBACK CHUB

P or T	#	Budget Description
T	1	Humpback chub natal origins. • Continue looking into non-lethal methods, and utilize humpback chub that are taken as a result of incidental take.
T	2	Continue LCR studies. • Lower 1200m effort discontinued, enhance existing spring and fall monitoring with remote sensing.
T	3	Effect of temperature vs. trout on humpback chub. • Continue existing studies and monitoring on the effect of temperature vs. trout on humpback chub.
T	4	Humpback chub aggregation monitoring, continue and add new sites. • Randomize sites, assess 2013/14 work • Utilize citizen science and remote tag readers
T	5	Increase humpback chub aggregations funding for monitoring. • Continue requirements of BO
T	6	Humpback chub mainstem aggregation enhancement by translocation. • Support pilot study.
T	7	More money to study the influence of turbidity on trout-humpback chub interactions. • Evaluate current research before moving forward, determine potential management actions to increase turbidity.
T	8	Support further development of the Yackulic humpback chub population model.
T	9	Support project, but also support proposed changes to reduce costs for Chute Falls translocations/monitoring.

MODELING

P or T	#	Budget Description
T	1	The following model elements need to be better understood (consider a workshop) to scope the utility and cost of developing a CRE ecosystem concept model to improve the predictive capability for effects of dam operations: • Fish studies (trout, chub, others)

		• Sediment transport • Hydrology • Foodbase • Recreation • Riparian ecology* • Nutrient budget* • Climate change* • Cultural values and perspectives/TEK* *these elements need considerably more information/instruction on how to incorporate these elements into a CRE ecosystem model.
T	2	Continue to develop research projects that would incorporate Traditional Ecological Knowledge (TEK) into CRE science and management and help contribute to management decisions.

FOOD BASE

P or T	#	Budget Description
T	1	The priority for developing food base projects should be a higher priority because of its potential importance to the CRE ecosystem in general and native fish recovery in particular.

NONNATIVES

P or T	#	Budget Description
T	1	Provide annual report and synthesis of nonnative invasive species monitoring data and options for monitoring and management. (fund with Experimental Fund)
T	2	Increase invasive species surveillance in the LCR and from Diamond down . (fund with Experimental Fund)
T	3	Review and synthesize data on tamarisk mortality impacts in the upper basin based on review of literature and on-going studies ($10K). DOI should consider whether this project is appropriate for the use of power revenues.

TROUT

P or T	#	Budget Description
T	1	Continue funding support to resolve questions about whether rainbow trout at the LCR originate from Glen Canyon. Provide additional funding to assess whether RBT reproduction is occurring in Marble canyon. Provide management recommendations.

T	2	Continue to fund Lees Ferry rainbow trout monitoring (electrofishing, RTELLS, and CREEL).
P	3	Evaluate the feasibility of options to maintain water quality (e.g., temperature) needed to support a quality trout fishery in Lees Ferry and native fish downstream (TCD, water management options etc.).
T	4	GCMRC should participate in the development of a more detailed fish management plan for Lees Ferry consistent with the NPS Comprehensive Fish management plan and other agency policies and mandates.
T	5	Provide funding to map the channel in Glen canyon and assess the effect of low flows on fish habitat.
T	6	Continue funding projects to assess competition and predation between Humpback chub & trout.
T	7	Continue to fund system-wide electrofishing monitoring for natives and nonnatives using techniques intended to be non-lethal.

PROGRAM PLANNING

P or T	#	Budget Description
T	1	GCDAMP administrative history funding. Proceed with proposed effort.
P	2	Cost for new GCMRC facility in Flagstaff. Devastating reduction of research due to increased USGS burden.
P	3	Utility of the POAHG - some funding may be appropriate, but review the costs and benefits - less money may be appropriate.
P	4	Role of Science Advisors in GCDAMP. TWG needs to be involved in the development of the role of the SAs, and SA budget may need to be increased.
T	5	PEP reviews should be funded in the budget, especially for trout, humpback chub, research and monitoring.
T	6	Cultural resources treatment plan, resolution of tribal issues related to treatment needs to occur. This needs to be resolved by DOI before budget is approved. This is needed to implement the new PA.
T	7	What are we "required" to do under the biological opinion for monitoring? Clarify for the TWG, the biological opinion requirements within the GCDAMP.

TWG Triennial Budget Input FY 2015–17
For consideration by BAHG on behalf of the TWG

CORE MONITORING

P or T	#	Budget Description
T	1	Core monitoring needs, Strategic Plan, and SSQs should be considered after LTEMP is completed.
T	2	Develop system model linking aquatic and terrestrial ecosystems. This is the framework on which core monitoring can be established. Establish a discussion in the FY15-16 time frame to learn how to undertake this effort - review other systems model (e.g., MSCP). After LTEMP approval, request review by SAs, etc. No significant budget implications at this stage, but FY16+ may involve SA review and project formulation.

NEW PROJECTS

P or T	#	Budget Description
P	1	Should the cost of AMWG river trips be a budget item, and if so, how many trips should be provided. This should be an AMWG decision.
T	2	Sand Bar Model. Develop it and peer review and fix it. LTEMP has attempted this, and not come up with a useful model. We think it would take too much money to fix this, and that high quality sand bar monitoring is sufficient for our program.
T	3	Driftwood (CWD) history, distribution, movement, HFE & normal flows (citizen science). Initial steps would be to think about projects, and implement with volunteers. For instance, river guides could try to recapture marked wood. Should only be a very small line item.
T	4	Need to understand impacts at historic properties. We need more information on this. A question of clarification: is this a permit issue?
T	5	Razorback sucker monitoring, need more funds for translocations and monitoring. Evaluate the adequacy of existing programs to determine whether this species needs more funding.
T	6	Discuss options for equalization that minimize resource degradation. Restatement of issue: Discuss options for scheduling equalization releases that minimize resource degradation. This should be a technical issue, and not a budget issue. We ask that this be placed on a future agenda.
T	7	Assess cataract canyon as a control for CRE DFCs. We encourage cooperative work without using AMP funding.

T	8	More money for work below Diamond Creek. Needs more clarification.
T	9	What is the question needing an answer regarding mapping habitats program? (320k) We need more discussion about this project and its objectives. We want to know more about all Lee Ferry's reach work. Refer back to TWG.

SUPPORT IN QUESTION

P or T	#	Budget Description
T	1	Can't support bat/bird/spider work. Need more information about this. Some of us like it just from the title, but some have concerns.
P	2	Reduce habitat map below GCD totally. We need more details and discussion about this project. Refer back to TWG.
P	3	Expansion of AMP into Powell and Mead, what is the funding source and is it legal? TWG and AMWG not qualified to make legal determination – if this is a concern, check with DOI solicitor office.
P	4	$500k for experimental carry over fund. TWG should discuss whether this fund be capped at some number.
P	5	Socioeconomic costs? Are more funds needed for unfunded science? Socioeconomic studies are appropriate and needed.
T	6	The increase in cultural resources work from $371k to over $500k does not seem justified, more info needed. This is an accounting change and not a real increase – formerly overhead costs are now being directly assigned to this work.
T	7	The socio-economic DSS work is a low priority. Clarification – this means Applied Decision Methods (ADM, not DSS). Needs more discussion. How does this fit in with work being done for LTEMP. Please justify.
T	8	How does socio-economics fit into the program? It is an important part of our program.
T	9	Reduce trout turbidity funding, pipeline. Clarification: the thought is, if there is nothing we can do to control turbidity, why study it. Needs more discussion.