Glen Canyon Dam Adaptive Management Work Group

Agenda Item Form

September 20, 2017

<u>Agenda Item</u>

FY2018-20 Triennial Budget and Work Plan

<u>Purpose of Agenda Item</u>

To make a recommendation to the Secretary on the FY2018-20 Triennial Budget and Work Plan (TWP) for the Glen Canyon Dam Adaptive Management Program (GCDAMP).

<u>Action Requested</u>

Motion requested. The following proposed motion is based on the recommendation from the Technical Work Group (TWG). However, no motion is presumed to be made unless and until an AMWG member makes the motion in accordance with the AMWG Operating Procedures.

> AMWG recommends to the Secretary of the Interior his approval of the GCDAMP FY 2017 budget as amended and recommended by TWG.

<u>Presenters</u>

David Braun, Sound Science LLC, GCDAMP Science Advisors Executive Coordinator
Shane Capron, Chair, Technical Work Group (TWG) Budget Ad Hoc Group (BAHG)
Katrina Grantz, Adaptive Management Group Chief, Upper Colorado Region, Bureau of Reclamation
Scott VanderKooi, Chief, Grand Canyon Monitoring and Research Center (GCMRC)

<u>Previous Action Taken</u>

✓ August 31, 2017: TWG passed the following motion by a vote of 10 yes, 1 no, and 2 abstaining:

The TWG recommends that the AMWG recommend for approval the Glen Canyon Adaptive Management Program Triennial Budget and Work Plan – Fiscal Years 2018-2020 (Draft August 17, 2017) to the Secretary of Interior with the following changes:

1. Approving GCMRC's Project C as written, contingent upon adding language to Reclamation's Project C.7., Experimental Vegetation Treatment, for funding tribal engagement as partners in planning and executing the experiment.
2. Approving GCMRC Project D with no funding for D.1, D.2, or D.3, but with funding for D.4.
3. GCMRC Project G.5 – Add one annual seining trip funded by the Native Fish Conservation Contingency Fund.
4. Approve GCMRC Project I with an additional Spring system-wide monitoring trip to I.1 and a Fall Diamond Down trip
5. GCMRC Project E. with reinsertion of Project E.7.1, Aquatic Vegetation Surveys, and Project E.7.2, Artificial Streams.

6. Without a net increase to the budget, add a new Project N, Hydropower, to the GCMRC work plan with work efforts that include (also add to Reclamation Project C with complementary language):
   a. Develop Glen Canyon Dam operational experiments to meet the hydropower objective.
   b. Consider and estimate impacts of experiments on hydropower as part of experimental design.
   c. Incorporate total hydropower value into Decision Support Systems being developed in GCMRC Project J.2
   d. Utilize WAPA and Reclamation hydropower data, as available, and include WAPA technical staff in the development of models, design of experiments, and monitoring metrics.
7. GCMRC Project J. Socioeconomics as written with additional language:
   a. Clarifying language will be added to Project J.2 that indicates integrating hydropower analysis into the modeling of trout management flows will be a primary focus. Incorporating hydropower analysis follows the development and integration of rainbow trout and humpback chub population models and cost-effectiveness analysis, used to identify efficient management actions to meet adult humpback chub abundance goals. Hydropower analysis in J.2 is an incremental step in the development of applied decision and scenario analysis research at GCMRC. Adding hydropower analysis into the applied decision and scenario analysis research is timely provided the proposed LTEMP EIS experiments, including trout management flows.
   b. A workshop will occur with GCMRC staff and GCDAMP stakeholders in fiscal year 2018 to review and discusses the trade-offs between trout management flows, expected downstream rainbow trout and humpback chub outcomes and associated costs of management actions, including hydropower. This workshop will provide an opportunity to explore opportunities to improve hydropower resources while meeting downstream rainbow trout and humpback chub resources goals as defined in the LTEMP EIS.
8. Approve Reclamation Project D. with addition of identifying how Reclamation Project D elements and GCMRC project elements address stipulations in the PA and track their progress.
9. Increase funding for Reclamation Project D.10 to a target balance of about $200,000 by the end of FY 2018.
10. Approve Reclamation Project C. with changes to allow allocation of some funds from Reclamation Project C.5 into Reclamation Project D.10.

<u>Relevant Science and Background Information</u>

✓ By TWG: On October 19, 2016, the Technical Work Group passed by consensus the GCDAMP Triennial Budget and Work Plan Process that is attached to this AIF.

Three additional documents will guide the development of the GCDAMP budget for the foreseeable future:

✓ On October 7, 2016, the Department of the Interior filed the Long-Term Experimental and Management Plan (LTEMP) Final Environmental Impact Statement (FEIS) with the U.S. Environmental Protection Agency. That FEIS can be found here: http://ltempeis.anl.gov/documents/final-eis/.

- ✓ On December 15, 2016 Secretary of the Interior Sally Jewell signed the LTEMP Record of Decision (ROD). It can be found here: http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.
- ✓ On Tuesday, January 17, 2017 the GCMRC LTEMP Science Plan was finalized. It can be found here: https://doi.org/10.3133/ofr20171006.

Summary of Presentation and Background Information

Process Overview

Every three years, the GCDAMP develops a Triennial Budget and Work Plan (TWP) to guide the annual budget process. The GCDAMP began using a TWP for the FY 2015-2017 work plan as directed by Secretary's Designee Anne Castle in a memo dated May 7, 2014. The memorandum also instructed the GCDAMP to revise the work planning guidance to reflect the development of three-year work plans. Secretary's Designee Jennifer Gimbel reiterated this direction in a July 8, 2016 memorandum to Scott VanderKooi and Katrina Grantz. The budget process document was revised and passed by consensus of the TWG in October of 2016, and is awaiting review by the AMWG. The GCDAMP and TWG utilized this budget process when developing the FY2018-2020 Budget and Work Plan.

The TWG Budget Ad Hoc Group (BAHG) is tasked to initiate this activity and to make a recommendation to the full TWG. The BAHG, chaired by Shane Capron, received the draft TWP on June 30. The BAHG then utilized a series of six conference calls to review the various projects from both GCMRC and BOR and develop comments. On August 4, Seth Shanahan (TWG Chair) provided a final set of consensus comments to GCMRC and BOR on the draft TWP. Also, individual TWG members provided comments as well that were not part of the consensus package from the BAHG. Thus, the BAHG report consists of the final comments provided on August 4.

On August 30-31, 2017 the full TWG considered the draft TWP and the comments and considerations of the BAHG and voted to recommend approval of the FY 2018-20 TWP with several changes. Discussions during the TWG meeting were extensive and reflective of a diverse set of opinions. Several recurring themes arose about the TWP and the process for recommending approval of the TWP, as broadly described below:

- The hiatus imposed on the program by the FACA suspension order compressed the timeline for the TWG to consider the TWP and led to increased stakeholder frustrations.
- After a substantial initial attempt, it was clear that a consensus recommendation was not achievable. Majority voting was used as a last resort but achieving consensus remains the goal moving forward.
- Voting was also used to evaluate support for certain individual project elements and proposed changes to project elements. Voting margins on these were often very small indicating substantial disagreement among stakeholders. .
- There was limited time for discussion to make recommendations about the budgeted amounts and how to use the resources that were recommended for reallocation.
- The availability of funding continues to limit the program from being more successful. Stakeholders supported obtaining non-GCDAMP funding for lower priority work and work that is weakly connected to dam operations.

- Stakeholders requested a review of the TWP to ensure that document adheres to the direction of the Grand Canyon Protection Act regarding the use of the Upper Colorado River Basin Fund (Basin Fund). Reclamation agreed to conduct this review.
- Some stakeholders expressed that the TWP lacked a clear and obvious process for gathering information across the work elements into a coherent whole-system perspective.
- Improved organization of project elements was requested to achieve cultural resource goals and compliance more successfully. Tribal representatives wished for more involvement in the development of project element methods and noted that additional funding is necessary for the expected future tribal involvement, either from other sources or through prioritization and reallocation of GCDAMP dollars
- GCMRC agreed to add work elements to address the hydropower resource goal.
- Annual work prioritization continues to be a challenge. A suggested potential solution was for some monitoring and research to occur less than annually but still being conducted effectively and maintaining continuity over the 20-year LTEMP term

Reclamation Budget and Work Plan Overview

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 (Reclamation) Upper Colorado Region 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 Reclamation, 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) 2018–2020 was largely developed in consideration of the Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) and on the basis of outcomes from previous work plans. Additional consideration was given to meeting commitments outlined in: (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 2016 USFWS Biological Opinion for the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) (2016 Opinion); and (3) Section 106 of the National Historic Preservation Act (NHPA) and the Draft 2016 Programmatic Agreement.
A consumer price index (CPI) of 1% was assumed for FY 2018, FY 2019, and FY 2020. The budget and work plan will be updated annually with the actual CPI for the upcoming year.

Adjustments to draft budget and workplan were made in response to feedback from the TWG and the BAHG throughout the budget development process. All recommendations resulting from the TWG meeting on August 30-31 have been addressed and incorporated in the draft issued September 12, 2017.

A summary table of Reclamation projects and budget items is provided below. For full details, please see the FY2018-2020 GCDMAP Budget and Work Plan.

			CPI	1%
Reclamation Adaptive Management Program Budget Summary FY2018-2020				
		2018	**2019**	**2020**
	GCDAMP Total (w/ 1% CPI)	**$ 11,025,454**	**$ 11,135,708**	**$ 11,247,066**
	Reclamation Total (20%)	$ 2,205,091	$ 2,227,142	$ 2,249,413
A	**Adaptive Management Work Group**	**$ 425,000**	**$ 428,750**	**$ 432,538**
	percent of BOR budget	**19%**	**19%**	**19%**
A.1	Adaptive Management Work Group Costs (BOR)	$ 220,000	$ 222,200	$ 224,422
A.2	AMWG Member Travel Reimbursement	$ 20,000	$ 20,200	$ 20,402
A.3	AMWG Reclamation Travel	$ 20,000	$ 20,200	$ 20,402
A.4	AMWG Facilitation Contract	$ 75,000	$ 75,750	$ 76,508
A.5	Public Outreach - Reclamation public affairs, POAG	$ 25,000	$ 25,250	$ 25,503
A.6	Public Outreach- Administrative History	$ 50,000	$ 50,000	$ 50,000
A.7	AMWG Other	$ 15,000	$ 15,150	$ 15,302
B	**Technical Working Group**	**$ 200,000**	**$ 202,000**	**$ 204,020**
	percent of BOR budget	**9%**	**9%**	**9%**
B.1	TWG Costs (BOR)	$ 120,000	$ 121,200	$ 122,412
B.2	TWG Member Travel Reimbursement	$ 25,000	$ 25,250	$ 25,503
B.3	TWG Reclamation Travel	$ 20,000	$ 20,200	$ 20,402
B.4	TWG Chair Reimbursement/Facilitation	$ 25,000	$ 25,250	$ 25,503
B.5	TWG Other	$ 10,000	$ 10,100	$ 10,201
C	**Program Admin, ESA Compliance, and Management Actions**	**$ 949,000**	**$ 984,370**	**$ 1,031,814**
	percent of BOR budget	**43%**	**44%**	**46%**
C.1	Administrative Support for NPS Permitting	$ 112,000	$ 113,120	$ 114,251
C.2	Contract Administration	$ 75,000	$ 75,750	$ 76,508
C.3	Integrated Stakeholder River Trip	$ -	$ 40,000	$ -
C.4	Science Advisors Program	$ 150,000	$ 151,500	$ 153,015
C.5	Experimental Management Fund	$ 400,000	$ 404,000	$ 408,040
C.6	Native Fish Conservation Contingency Fund	carryover from previous years		
C.7	Experimental Vegetation Treatment	$ 145,000	$ 200,000	$ 220,000
C.8	Evaluation of means to prevent fish passage through GCD	$ -		$ 50,000
C.9	Evaluation of temperature control methods at GCD	$ 50,000		
C.10	Ridgway Rail and Southwest Willow Flycatcher monitoring	$ 17,000	$ -	$ 10,000

D	Cultural Resources	$ 631,000	$ 611,450	$ 581,030
	percent of BOR budget	29%	27%	26%
D.1	Reclamation Cultural Resources Program Management	$ 120,000	$ 121,200	$ 122,412
D.2	Support to Reclamation for cultural resources compliance	$ 150,000	$ 40,000	$ 40,400
D.3	Cultural Resources Monitoring - Grand Canyon	$ 47,000	$ 48,000	$ 48,000
D.4	Cultural Resources Monitoring - Glen Canyon	$ 34,000	$ 25,000	$ 26,000
D.5	Documentation of Navajo, Hualapai, and Paiute TCPs	$ 30,000	$ -	$ -
D.6	Associative values studies for TCPs	$ -	$ 100,000	$ 100,000
D.7	Cultural sensitivity training development - tribal expertise	$ 10,000	$ 15,000	$ 15,000
D.8	Cultural sensitivity training video	$ -	$ 20,000	$ 25,000
D.9	Hualapai archive project	$ 40,000	$ 40,000	$ -
D.10	Contingency fund for NHPA section 106 compliance	$ 25,000	$ 25,500	$ 25,700
D.11	Tribal cultural resources monitoring	$ 175,000	$ 176,750	$ 178,518
D.12	*Tribal participation in AMP (not funded by power revenues)*	*$ 475,000*	*$ 475,000*	*$ 475,000*
TOTAL Anctipated Available to Reclamation (w/ 1% CPI)		**$ 2,205,091**	**$ 2,227,142**	**$ 2,249,413**
TOTAL Reclamation Budget (Draft 2)		**$ 2,205,000**	**$ 2,226,570**	**$ 2,249,401**
	(Over) / Under budget	$ 91	$ 572	$ 12

Science Advisors Program Budget and Work Plan

The budget and work plan for the Science Advisors Program (SAP) is included under the Reclamation budget and work plan, Project C.4. The SAP work plan has five components:

(1) supporting the three-year Knowledge Assessment process;
(2) establishing a standing panel of five year-round Science Advisors to provide several critical expert peer-review services, mostly on a three-year cycle leading up to the next Knowledge Assessment and Triennial Work Plan;
(3) organizing one or two independent, external panel reviews focused on topics for which the GCMRC, TWG, AMWG, and/or Secretary's Designee need(s) independent review and recommendations, prioritized in consultation with the Bureau of Reclamation;
(4) maintaining routine interactions with the GCMRC, TWG, and AMWG to sustain the ability of the Executive Coordinator ensure effective Science Advisor Program support of the AMP; and
(5) maintaining routine Science Advisors Program administration.

These efforts are budgeted at $150,000/year + CPI.

GCMRC Budget and Work Plan Overview

In fiscal years 2018, 2019, and 2020 (FY2018–20), the GCMRC and its cooperators will undertake monitoring and research activities that, in response to the legal requirements of the Grand Canyon Protection Act (GCPA) and the recently approved LTEMP, will monitor the status and trends of natural, cultural, and recreational resources of the Colorado River ecosystem between Glen Canyon Dam and Lake Mead reservoir.

The total recommended budget of GCMRC in FY2018 is $9.02 million. Funding for this amount includes $8.82 million from GCDAMP funds, an additional $0.19 million from other Reclamation funding sources, including $.04 million for native fish projects from the Native Fish Conservation Contingency Fund, and $0.33 million in funds carried forward from FY2017.

The total recommended budget of GCMRC in FY2019 is $9.21 million. Funding for this amount includes $8.9 million from GCDAMP funds, $0.17 million from anticipated GCMRC carryover funds, and an additional $0.36 million from other Reclamation funding sources, including $0.29 million for native fish projects from the Native Fish Conservation Contingency Fund.

The total recommended budget of GCMRC in FY2020 is $9.19 million. Funding for this amount includes $8.99 million from GCDAMP funds, $0.09 million from anticipated GCMRC carryover funds, and an additional $0.14 million for native fish projects from the Native Fish Conservation Contingency Fund.

As in the previous work plan, most work for FY2018-20 is focused on the aquatic ecosystem, sediment transport, and hydrology. Budget proportions by resource area only vary slightly by year with approximately 43% to be allocated to monitoring and research work in aquatic ecology and fisheries and 25% to projects in geomorphology, stream flow monitoring, sediment transport, and water quality. Smaller proportions, from approximately 6% to 0.1% each, are directed to work in riparian ecology, geospatial science and remote sensing, cultural and archaeological resources, socioeconomics, and hydropower. Direct GCMRC administrative costs are 16% of the budget.

Overhead rates for GCDAMP funds expended by GCMRC are projected to be 15.557% in FY2018 and 26% in FY2019 and FY2020. The rate for funds transferred to cooperating agencies will remain 3%. The increases listed above are due to expected higher facility costs associated with a new building. The City of Flagstaff, from whom USGS leases space, has determined that GCMRC's current building has outlived its useful lifespan and must be replaced. Current projections are to move into this yet to be built facility in summer 2018. Increases in overhead will result in less funding available for science activities. Despite this, the USGS is required by law to recover full costs associated with conducting reimbursable work. Overhead rates are calculated by GCMRC's parent organization, the Southwest Biological Science Center (SBSC), and varies year to year depending on funding levels and Center costs. With approvals, USGS allows reduced overhead rates to be charged as is done for funding from the GCDAMP. In those cases, SBSC is required to make up the difference between funding generated from that reduced rate and actual costs with appropriated funds (known as "cost-share" by USGS). To cover this cost-share in support of GCMRC's work for the GCDAMP, the USGS contributes approximately $1,000,000 in appropriated funds per year to SBSC. This funding is not a certainty and periodically SBSC is required to submit justifications to USGS leadership for this continued support. The most recent justification was required in August 2016. Were this cost-share funding to decrease or be eliminated, GCMRC would be forced to charge higher overhead rates for GCDAMP funding and thus further reduce the amount of money available for science.

GCMRC made changes to the FY18-20 work plan in response to the TWG motion. The motion that was approved by a majority vote of TWG members present at the meeting included a list of 10 changes to the work plan, four for Reclamation projects and six for GCMRC projects. For GCMRC projects, these included eliminating elements from Project D, adding back research elements to Project E, and restoring several fish monitoring trips to Projects G and I. In addition, the lack of emphasis on the Hydropower LTEMP Resource Goal was noted and addressed by adding work to Project J and creating Project N. Based on the language in the approved motion, Reclamation and GCMRC developed the final draft of the FY2018-20 TWP for consideration by the AMWG. This draft incorporates all the changes from the TWG motion for GCMRC projects with one exception.

Project element D.1, Geomorphic Effects of Dam Operations and Vegetation Management, was retained in order to meet GCMRC's obligation to provide relevant scientific information in support of the Archaeological and Cultural Resources LTEMP Resource Goal. We also chose to retain this element given the need to evaluate the condition of key resources, including historic properties and traditional cultural properties, before any experiment identified in the LTEMP ROD is implemented. Monitoring for long-term unacceptable adverse impacts to key resources, again including historic properties and traditional cultural properties, is required since this serves as the criteria to off ramp any of the experiments to be conducted under the LTMEP ROD.

Grand Canyon Monitoring and Research Center

FY 2018-20 Project Budgets

Project	Project Description	FY18-20 Summary		
		FY18	**FY19**	**FY20**
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***	$1,229,646	$1,251,097	$1,317,861
B	***Sandbar and Sediment Storage Monitoring and Research***	$1,039,115	$1,110,925	$1,043,962
C	***Riparian Vegetation Monitoring and Research***	$584,657	$485,251	$456,692
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***	$261,903	$293,737	$297,905
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***	$342,754	$232,715	$256,724
F	***Aquatic Invertebrate Ecology***	$771,248	$811,143	$779,902
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***	$1,506,095	$1,674,368	$1,681,653
H	***Salmonid Research and Monitoring***	$683,065	$725,679	$698,640
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***	$557,090	$581,299	$577,347
J	***Socioeconomic Research in the Colorado River Ecosystem***	$281,305	$252,145	$257,956
K	***Geospatial Science and Technology***	$301,934	$230,728	$273,214
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***	$75,000	$75,000	$75,000
M	***Administration***	$1,375,086	$1,477,793	$1,572,834
N	***Hydropower Monitoring & Research***	$11,956	$13,482	$13,845
	GCMRC AMP Total	**$9,020,855**	**$9,215,361**	**$9,303,535**
	Anticipated GCMRC AMP Funds (80%)	**$8,820,363**	**$8,908,567**	**$8,997,653**
	Over/Under Budget	**($200,492)**	**($306,794)**	**($305,882)**
	Native Fish Conservation Contingency Fund	$43,000	$294,000	$145,000
	Anticipated Carryover (From Previous FY)	$332,000	$174,508	$161,713
	GCMRC AMP Total Over/Under Budget (w/Fish Funds & Carryover)	**$174,508**	**$161,713**	**$832**
	Lake Powell	$150,000	$70,924	$0
	GCMRC Grand Total (w/ Lake Powell)	**$9,170,855**	**$9,286,285**	**$9,303,535**

USGS
science for a changing world

Prepared in cooperation with
the Glen Canyon Dam Adaptive
Management Program

Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2018–2020

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

Final AMWG Draft:
September 11, 2017

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

Cover: View of the Colorado River in lower Marble Canyon near the Little Colorado River confluence, Grand Canyon National Park, Scott VanderKooi, U.S. Geological Survey.

Prepared in cooperation with the Glen Canyon Dam Adaptive Management Program

Glen Canyon Dam Adaptive Management Program Biennial Budget and Work Plan—Fiscal Years 2018–2020

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

Final AMWG Draft: September 11, 2017

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

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Abbreviations

AGFD: Arizona Game and Fish Department
AIS: Aquatic invasive species
AZDEQ: Arizona Department of Environmental Quality
BACI-based analysis: Before-After-Control-Impact experiment design
BAHG: Budget ad hoc group
BiOp: Biological Opinion
CE-QUAL-W2: A water quality and hydrodynamic model
CHIRP: Frequency-modulated echosounder system
CPUE: Catch-per-unit-effort
CRe: Colorado River ecosystem
DASA: Data Acquisition, Storage, and Analysis Program
DEMs: Digital elevation models
DOE: Department of Energy
DOI: Department of Interior
DSM: Digital surface model
eDNA: Environmental DNA
EGC: Eastern Grand Canyon
EIS: Environmental Impact Statement
EPT: Aquatic insect orders Ephemeroptera, Plecoptera, Trichoptera
EROS: USGS Earth Resources Observation and Science Center
FACA: Federal Advisory Committee Act
FGDC: Federal Geographic Data Committee
FLIR: Forward looking infrared radar camera
FY: Fiscal year
GCD: Glen Canyon Dam
GCDAMP: Glen Canyon Dam Adaptive Management Program
GCMRC: Grand Canyon Monitoring and Research Center
GCNP: Grand Canyon National Park
GCPA: Grand Canyon Protection Act
GIS: Geographical information systems
GLCA: Glen Canyon National Recreation Area
GNSS: Global navigation satellite system
HFE: High-flow experiment
ISCO samplers: Water monitoring samplers
JCM: Juvenile chub monitoring
LCR: Little Colorado River
LTEMP: Long-term experimental and management plan
NGSIDB: National Geodetic Survey integrated database
NO: Natal origins of rainbow trout
NPS: National Park Service
NSSDA: National Standard for Spatial Data Accuracy
NWIS: National Water Information System
OWI: USGS Office of Water Information
PA: Programmatic agreement
PEP: Protocol Evaluation Panel
PIT-tag: Passive integrated transponder electronic tag
RAMPS: Restoration Assessment and Monitoring Program
RM: River mile
ROD: Record of Decision
RTELSS: Rainbow trout early life stage studies
SCADA: Supervisory Control and Data Acquisition
SMBI: Sand mass balance index
SRP: Soluble reactive phosphorous
TELS: Trout early life stage
TMFs: Trout management flows
TRGD: Trout reproductive and growth demographics
TWG: Technical Work Group
TWP: Triennial work plan
USFWS: U.S. Fish and Wildlife Service
USGS: U.S. Geological Survey
VIE: Visible implant elastomer tags
YOY: Young-of-year

Chapter 1. Bureau of Reclamation Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2018–2020

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 (Reclamation) Upper Colorado Region 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 Reclamation, 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) 2018–2020 was largely developed in consideration of the Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) and on the basis of outcomes from previous work plans. Additional consideration was given to meeting commitments outlined in: (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 2016 USFWS Biological Opinion for the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) (2016 Opinion); and (3) Section 106 of the National Historic Preservation Act (NHPA) and the Draft 2016 Programmatic Agreement.

A consumer price index (CPI) of 1% was assumed for FY 2018, FY 2019, and FY 2020. The budget and work plan will be updated annually with the actual CPI for the upcoming year.

A. Adaptive Management Work Group (AMWG) Costs

A.1. AMWG Program Management

This budget represents Reclamation 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 Reclamation's web pages. Reclamation 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. Reclamation also organizes stakeholder travel to AMWG meetings, 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.

Reclamation 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). Reclamation staff will provide budget information to the AMWG on a regular basis. Completed AMWG work products will be of high quality and promptly distributed to AMWG members/alternates and interested parties.

Budget: FY18 = $220,000 FY19 = $222,200 FY20 = $224,422

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 and support their attendance at all meetings. Many members live outside of Phoenix or Flagstaff Arizona, where meetings are often held. As a result, many members must incur travel costs. Having Reclamation 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 cars increases opportunities for members to participate in a variety of AMWG assignments. Because Reclamation can purchase airline tickets at the Federal Government rate, there are cost savings to the program.

The GCDAMP benefits from having all AMWG members participating in regularly scheduled meetings. The AMWG is made up of a group of diverse and committed stakeholders that span the resources and values of Glen Canyon Dam and Glen and Grand Canyon below. The AMWG provides a forum of discussion for bringing key issues to resolution. As a collective body, the AMWG provides scientifically informed and broadly supported recommendations to the Secretary of the Interior regarding the operation of GCD and other management actions.

Budget: FY18= $20,000 FY19 = $20,200 FY20 = $20,402

A.3. AMWG Reclamation Travel

This budget supports travel expenses Reclamation staff incur to attend AMWG and ad hoc group meetings and AMWG related coordination. The primary goal is for Reclamation staff to be able to travel to meetings and participate in completing AMWG assignments. By doing so, the program benefits from greater interaction between Reclamation staff and GCDAMP stakeholders.

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

***Budget*:** FY18= $20,000 FY19 = $20,200 FY20 = $20,402

A.4. AMWG Facilitation Contract

This budget supports a facilitator who is under contract to Reclamation to provide facilitation services for AMWG meetings. The facilitator may also assist AMWG ad hoc groups or TWG 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. In addition the facilitator assists Reclamation in coordinating meetings and developing agendas, and provides follow up after meetings that include action items and meeting minutes.

***Budget*:** FY18= $75,000 FY19 = $75,750 FY20 = $76,508

A.5. Public Outreach - Public Affairs and Public Outreach Ad Hoc Group

This budget covers the expenses for Reclamation staff and the Public Outreach Ad Hoc Group (POAHG) to develop materials for the GCDAMP public outreach efforts. This item also includes Reclamation public affairs staff attendance at AMWG meetings.

Reclamation public affairs staff and the POAHG, as appropriate, will work to develop materials to inform and educate the public on the goals and administration of the GCDAMP.

Products may 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.

Budget: FY18= $25,000 FY19 = $25,250 FY20 = $25,503

A.6. Public Outreach – Administrative History Project

The GCDAMP was initiated in 1996 and despite consistent record documentation and retention, the administrative portion of the program has not been synthesized in a manner that allows an easy review of the progression of ideas, discussion topics, research, recommendations, decisions and achievements over time. New members of TWG and AMWG and other interested parties, also need concise, accessible orientation materials that provide an overview of GCDAMP, the stakeholders, and past actions the program has taken.

The Administrative History Project implements goals of the Public Outreach Ad Hoc Group by providing a better understanding of the history of the GCDAMP, its work, and participants. The project, which began in FY2017, is anticipated to continue through FY2021, and undertake the following:

- Develop oral histories and interviews with GCDAMP 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 GCDAMP.

Budget: FY18 = $50,000 FY19 = $50,000 FY20 = $50,000

A.7. AMWG Other

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

- Meeting room rentals
- Overnight mailings of AMWG meeting packets
- Copying of reports
- Purchasing meeting materials (cassette tapes, markers, paper, etc.)
- Purchasing audio visual equipment (microphones, cords, phones, projector, etc).

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: FY18 = $15,000 FY19 = $15,150 FY20 = $15,302

Table 1. Reclamation Adaptive Management Work Group Budget Summary

	Fiscal Year 2018					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
A	**Adaptive Management Work Group**					**$ 425,000**
A.1	Adaptive Management Work Group Costs (BOR)	$ 220,000				$ 220,000
A.2	AMWG Member Travel Reimbursement		$ 20,000			$ 20,000
A.3	AMWG Reclamation Travel		$ 20,000			$ 20,000
A.4	AMWG Facilitation Contract				$ 75,000	$ 75,000
A.5	Public Outreach - Reclamation public affairs, POAG	$ 25,000				$ 25,000
A.6	Public Outreach- Administrative History				$ 50,000	$ 50,000
A.7	AMWG Other			$ 15,000		$ 15,000
A	**Total Fiscal Year 2018**	**$ 245,000**	**$ 40,000**	**$ 15,000**	**$ 125,000**	**$ 425,000**

	Fiscal Year 2019					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
A	**Adaptive Management Work Group**					**$ 428,750**
A.1	Adaptive Management Work Group Costs (BOR)	$ 222,200				$ 222,200
A.2	AMWG Member Travel Reimbursement		$ 20,200			$ 20,200
A.3	AMWG Reclamation Travel		$ 20,200			$ 20,200
A.4	AMWG Facilitation Contract				$ 75,750	$ 75,750
A.5	Public Outreach - Reclamation public affairs, POAG	$ 25,250				$ 25,250
A.6	Public Outreach- Administrative History				$ 50,000	$ 50,000
A.7	AMWG Other			$ 15,150		$ 15,150
A	**Total**	**$ 247,450**	**$ 40,400**	**$ 15,150**	**$ 125,750**	**$ 428,750**

	Fiscal Year 2019					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
A	**Adaptive Management Work Group**					**$ 432,538**
A.1	Adaptive Management Work Group Costs (BOR)	$ 224,422				$ 224,422
A.2	AMWG Member Travel Reimbursement		$ 20,402			$ 20,402
A.3	AMWG Reclamation Travel		$ 20,402			$ 20,402
A.4	AMWG Facilitation Contract				$ 76,508	$ 76,508
A.5	Public Outreach - Reclamation public affairs, POAG	$ 25,503				$ 25,503
A.6	Public Outreach- Administrative History				$ 50,000	$ 50,000
A.7	AMWG Other			$ 15,302		$ 15,302
A	**Total**	**$ 249,925**	**$ 40,804**	**$ 15,302**	**$ 126,508**	**$ 432,538**

B. Technical Work Group (TWG) Costs

B.1. TWG Program Management

This budget represents Reclamation 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 Reclamation maintains for the program. Reclamation 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. Reclamation staff will provide budget information to the TWG on a regular basis. Completed TWG work products will be promptly distributed to TWG members/alternates and interested parties.

Budget: FY18 = $120,000 FY19 = $121,200 FY20 = $122,412

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 and support 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 Reclamation can purchase airline tickets at the Federal Government rate, there are 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 that incorporate the best scientific information available to the GCDAMP. It is important to support participation of all TWG members in regularly scheduled meetings so that they can stay abreast of TWG-related activities and the research and monitoring in the GCDAMP.

Budget: FY18 = $25,000 FY19 = $25,250 FY20 = $25,503

B.3. TWG Reclamation Travel

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

Budget: FY15 = $20,000 FY16 = $20,200 FY17 = $20,402

B.4. TWG Chair Reimbursement/Facilitation

This budget supports a person who is under contract to Reclamation to serve as the chairperson for the TWG. This person may also assist AMWG/TWG ad hoc groups in completing assignments.

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 Reclamation 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.

In the event that the TWG chair salary is covered through funding outside the GCDAMP, these funds can be used by Reclamation for TWG-related administrative purposes or to cover facilitation and support for TWG-related issues. Part, or all, of this budget may be used for facilitation services for TWG meetings, support for TWG ad hoc groups, or support completing TWG assignments.

Budget: FY15 = $25,000 FY16 = $25,250 FY17 = $25,503

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 AMWG meeting packets
- Copying of reports
- Purchasing meeting materials (cassette tapes, markers, paper, etc.)
- Purchasing audio visual equipment (microphones, cords, phones, projector, etc)

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. It is expected that most, if not all, TWG meetings will be held at venues that do not incur additional costs to the GCDAMP. Other expenses will be kept to a minimum in an effort to keep within the GCDAMP budget.

Budget: FY18 = $10,000 FY19 = $10,100 FY20 = $10,201

Table 2. Reclamation Technical Work Group Budget Summary

	Fiscal Year 2018					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
B	**Technical Working Group**					**$ 200,000**
B.1	TWG Costs (BOR)	$ 120,000				$ 120,000
B.2	TWG Member Travel Reimbursement		$ 25,000			$ 25,000
B.3	TWG Reclamation Travel		$ 20,000			$ 20,000
B.4	TWG Chair Reimbursement/Facilitation				$ 25,000	$ 25,000
B.5	TWG Other			$ 10,000		$ 10,000
B	**Total Fiscal Year 2018**	**$ 120,000**	**$ 45,000**	**$ 10,000**	**$ 25,000**	**$ 200,000**

	Fiscal Year 2019					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
B	**Technical Working Group**					**$ 202,000**
B.1	TWG Costs (BOR)	$ 121,200				$ 121,200
B.2	TWG Member Travel Reimbursement		$ 25,250			$ 25,250
B.3	TWG Reclamation Travel		$ 20,200			$ 20,200
B.4	TWG Chair Reimbursement/Facilitation				$ 25,250	$ 25,250
B.5	TWG Other			$ 10,100		$ 10,100
B	**Total Fiscal Year 2019**	**$ 121,200**	**$ 45,450**	**$ 10,100**	**$ 25,250**	**$ 202,000**

	Fiscal Year 2020					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
B	**Technical Working Group**					**$ 204,020**
B.1	TWG Costs (BOR)	$ 122,412				$ 122,412
B.2	TWG Member Travel Reimbursement		$ 25,503			$ 25,503
B.3	TWG Reclamation Travel		$ 20,402			$ 20,402
B.4	TWG Chair Reimbursement/Facilitation				$ 25,503	$ 25,503
B.5	TWG Other			$ 10,201		$ 10,201
B	**Total Fiscal Year 2020**	**$ 122,412**	**$ 45,905**	**$ 10,201**	**$ 25,503**	**$ 204,020**

C. Program Administration, ESA Compliance, and Management Actions

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 other staff who review all proposals for projects to be completed in the park and to determine NEPA, ESA and NHPA compliance requirements. 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: FY18 = $112,000 FY19= $113,120 FY20 = $114,251

C.2. Contract Administration

This budget covers the expenses for Reclamation acquisitions and contracting staff to prepare and execute contracts associated with the GCDAMP. Specifically, these contracts include GCMRC science and monitoring, NPS monitoring and permitting, AMWG facilitation, TWG chairperson reimbursement, Science Advisors program, Tribal participation and resource monitoring, Administrative History, and programmatic agreement (PA) contract work.

Reclamation contract specialists will accurately apply funds spent on individual contracts to ensure costs do not exceed contract limits. They will keep the Reclamation Environmental Resources Division (ERD) contracting technical representative informed as to those charges so accurate reporting can be made to both AMWG and TWG members.

Reclamation contracting technical representatives 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 Reclamation staff informed of discrepancies or concerns. Work will be completed on time and within the limits of the contract.

Budget: FY18 = $75,000 FY19 = $75,750 FY20 = $76,508

C.3. Integrated GCDAMP Stakeholder River Trip

The objective of this project is to provide an opportunity for AMWG members and GCDAMP stakeholders to articulate their respective values, concerns and issues in a field setting. The river trip also provides the opportunity for AMWG members to visit the canyon and gain a greater understanding of GCDAMP resources and issues. The river trip will be agenda-driven and is intended to provide an opportunity for GCDAMP stakeholders to share perspectives about their values and positions respective to the Grand Canyon and the Colorado River. It is expected that one trip every 2 or 3 years is the appropriate frequency.

Budget: FY18 =$0 FY19 = $40,000 FY20 = $0

C.4. Science Advisor Program

This budget provides funding to support the Science Advisor Program, including the office of the Executive Coordinator for the Science Advisor Program. The Science Advisor Program provides recommendations to the AMWG and the GCMRC regarding research and monitoring priorities, knowledge integration, and the adaptive management of natural, cultural, and recreational resources affected by Glen Canyon Dam operations and associated adaptive management actions. As part of this effort, the Science Advisor Program periodically conducts independent, external reviews of GCDAMP resource-specific monitoring and research programs, and carries out other advisory tasks as requested by the AMWG. The Executive Coordinator manages the Science Advisor Program and may also carry out advisory tasks.

Tasks identified for the FY2018-2020 work plan are:

1) Support and guide the three-year Knowledge Assessment process, including: (a) advising and guiding a review and updating of methods during FY 2019 while ensuring continuity of methods and data compatibility, (b) advising and guiding the assessment itself during the first half of FY 2020, and (c) integrating and analyzing the results of the FY 2020 assessment and its implications for the next (FY 2021-2023) triennial work plan, all in close coordination with the TWG and GCMRC. Est. cost: $8,000 in FY 2018, $20,000 in FY 2019, $45,000 in FY 2020.

2) Establish a standing panel of five year-round Science Advisors managed by the Executive Coordinator. This standing panel will: (a) review the Annual Reporting Meeting presentations, annual reports, and three-year Knowledge Assessment, to provide feedback to the TWG and GCMRC on annual work plans and the next (FY 2021-2023) triennial work plan; and (b) provide recommendations for organizing and recruiting experts for independent external reviews (see below). It will take some time to get the panel established during FY 2018, while the Executive Coordinator: (a) develops a charter and set of guidelines for the standing panel – e.g., covering panelist responsibilities, appointment terms, compliance with OMB guidelines for federal peer review panels, etc. – in consultation with the GCMRC, TWG, and AMWG, and (b) recruits and initiates the activities of the first panel. Est. cost: $42,000/year + CPI for all three years.

3) Coordinate and conduct one or two external reviews focused on topics for which the GCMRC, TWG, AMWG, and/or Secretary's Designee need(s) independent review and recommendations. The Executive Coordinator will: (a) identify and prioritize potential

independent review topics for FY 2018-2020 based on AMP priorities in consultation with the GCMRC, TWG, and AMWG, (b) establish and manage independent review panels focused on one or two of the identified priority topics consistent with OMB guidelines for federal peer review panels, and (c) organize and ensure the delivery of reports on these reviews to the GCMRC, TWG, AMWG, and Secretary's Designee. It is anticipated that FY2018 would focus on identification and planning for the external review(s), while FY2019 would focus on the implementation and FY2020 would implement any wrap-up or planning for future external review(s). Est. average annual cost: $24,000/year ($40,000 in FY 2018; $28,480 in FY 2019; and $3,965 in FY 2020)

4) Maintain routine interactions with the GCMRC, TWG, and AMWG to maintain full currency of the Executive Coordinator in the actions, knowledge systems, and emerging ideas of the GCDAMP to ensure effective Science Advisor Program support of the AMP. This task includes Executive Coordinator attendance at a reasonable number of meetings in person and the rest via web link. Est. cost: $40,000/year + CPI.

5) Maintain routine program administration, including regular communications with Reclamation, financial management, and archiving of records. Est. cost: $20,000/year + CPI.

Table 3. Science Advisors Program Budget Summary

SCIENCE ADVISORS PROGRAM	2018	2019	2020
1. Knowledge assessment	$ 8,000	$ 20,000	$ 45,000
2. Standing pannel	$ 42,000	$ 42,420	$ 42,844
3. External review(s)	$ 40,000	$ 28,480	$ 3,965
4. Exec coordinator work w/ GCDAMP	$ 40,000	$ 40,400	$ 40,804
5. Program administration	$ 20,000	$ 20,200	$ 20,402
TOTAL	**$150,000**	**$151,500**	**$153,015**

Budget: FY18 = $150,000 FY19 = $151,500 FY20 = $153,015

C.5. Experimental Management Fund

This budget item reserves funds for conducting experiments or management actions within the GCDAMP, with priority given to LTEMP-related experiments and management actions that could not be anticipated in advance of the three year budget and work plan and require timely implementation. The funds will be available to conduct experiments or management actions when conditions are appropriate. Reclamation will work with DOI agencies, the BAHG and TWG to identify projects that may be appropriate for the Experimental Management Fund. Each year, Reclamation will discuss with the TWG the possible projects or experiments for the upcoming year that may utilize the Experimental Management Fund. Projects that may utilize funds in the Experimental Management Fund include, but are not limited to, additional monitoring in the event of an extended duration fall HFE, additional experimentation related to native fish conservation and/or nonnative fish control, and other newly pressing scientific questions in the GCDAMP. If the funds allocated to the Experimental Management Fund are not needed in a given year, at the end of the year, they will be transferred to the Native Fish Conservation Contingency Fund (Reclamation project C.6); some year-end experimental management funds may also be allocated to the Contingency Fund for NHPA Section 106 Compliance (Reclamation project D.10).

Budget: FY18 =$400,000 FY19 = $404,000 FY20 = $408,040

C.6. Native Fish Conservation Contingency Fund

This budget item tracks the native fish conservation contingency fund. The goal of this budget item is to ensure that funds are available for native fish conservation actions or nonnative fish control the event this conservation action is needed for endangered humpback chub in accordance with Reclamation's ESA compliance obligations. This is a fund consisting of GCDAMP carryover funds from prior years and serves to ensure that funds are available for the conservation actions should the need arise. This first priority for use of these funds is to implement conservation actions as defined in the 2007 and 2016 biological opinions. Should excess funds become available beyond those needed for conservation actions, these funds could be expended on other research, monitoring, and management actions that help conserve native fish. In past years, Reclamation has targeted a balance of approximately $1M to $1.5M in the Native Fish Conservation Contingency Fund given anticipated conservation actions and the status of native and nonnative fish. Should anticipated conservation actions and/or the status of native and nonnative fish significantly change, Reclamation may adjust the target balance of the fund. This fund is anticipated to be incrementally increased with future carryover dollars, when available.

Carryover balance:

- End of FY16 carryover = $1,060,000
- End of FY17 anticipated carryover = Approximately $1,400,000

C.7. Experimental Vegetation Treatment

As described in the LTEMP Record of Decision, experimental riparian vegetation treatment is included as mitigation for dam operations within the Colorado River Ecosystem (CRE). Vegetation treatment actions on NPS managed lands will be implemented by NPS consistent with NPS *Management Policies* (NPS 2006) and consistent with the goals and objectives of LTEMP ROD. This will occur only within the CRE in areas that are influenced by dam operations. The NPS will work with tribal partners and GCMRC to experimentally implement and evaluate a number of vegetation control and native replanting activities on the riparian vegetation within the CRE in Grand Canyon National Park and Glen Canyon National Recreation Area. (GCRMC project C.4 describes GCMRC's coordination with NPS and tribal partners in developing the scientific design, implementation and monitoring protocols for the experimental vegetation treatment.) These activities would include ongoing monitoring and removal of selected nonnative plants, species in the corridor, systematic removal of nonnative vegetation at targeted sites, and native replanting at targeted sites and subreaches, which may include complete removal of tamarisk (both live and dead) and revegetation with native vegetation. Treatments fall into two broad categories, including the control of nonnative plant species and revegetation with native plant species. Principal elements of this experimental riparian vegetation proposal include:

- Control nonnative plant species affected by dam operations, including tamarisk and other highly invasive species;
- Develop native plant materials for replanting through partnerships and the use of regional greenhouses;
- Replant native plant species to priority sites along the river corridor, including native species of interest to Tribes;
- Remove vegetation encroaching on campsites; and
- Manage vegetation to assist with cultural site protection.

The first year will involve primarily planning and coordination for Grand Canyon to select pilot sites and coordinate with GCMRC and tribes. The second and third years for Grand Canyon will focus primarily on vegetation removal for campsite encroachment and of nonnative plants close to campsites as well as establishing plant propagation for future revegetation. Glen Canyon will focus primarily on nonnative removal in the first three years.

The project area is from Glen Canyon dam to Pearce Ferry. Project partners are the National Park Service, associated tribes, GCMRC, Bureau of Reclamation, youth corps and volunteers.

Project costs include project coordination, planning and administration costs (including an annual coordination and planning meeting for NPS, GCMRC and tribes; GCMRC vegetation data processing and transfer to NPS), personnel costs (NPS seasonal and term biological technicians for field work, data entry and reporting; NPS term archeologist for on-site field work, GIS and data staff support; funding tribal staff for tribal engagement as partners in planning and executing the experiment and for tribal on-site field work), supplies (tools and herbicides, plant propagation, fuel for boat travel), and contracts, agreements and river support (cooperative agreement for greenhouse operation costs, river support for field work, youth crew agreement to support field work). NPS will explore additional sources of funding external to the program to assist in funding tribal partners.

Year	GRCA	GLCA
Year 1: Oct 1, 2017- Sept 30, 2018	• Review the value, data, and rationale components for selecting Priority Treatment Areas • Review the current list and map of Priority Treatment Areas, and decide whether to revise based on each of the vegetation management objectives • Develop propagation materials plans, testing and partnerships • Review vegetation inventory and mapping data and compile comprehensive inter-agency list and database (e.g., beginning with Table 3 in this doc and identifying other new/pending datasets) • Assess outcomes from past treatments and identify best practices from other relevant locations • Assess GRCA CRMP campsite data and GCMRC veg monitoring information • Establish a suite of appropriate pilot areas for work in Year 2, and collect pre-treatment data • Consult and coordinate with tribes • Develop monitoring plan with GCMRC • Develop long-term experimental vegetation treatment plan	• Develop propagation materials plans and partnerships • Restore RM -7L recreation area (primarily tamarisk removal and replant natives; 5-10 acres), • Develop monitoring plan with GCMRC (Goals 1-3). • Develop long-term experimental vegetation treatment plan

Year	GRCA	GLCA
Year 2: Oct 1, 2018- Sept 30, 2019	• Continue propagation materials plans, testing and partnerships • Continue pilot project testing and monitoring at 1-2 sites within GRCA • Identify priority restoration sites based upon criteria listed in Table 3 with a focus on campsite encroachment as the highest priority for the initial phases • Engage Tribal partners and GCMRC in site selection • Develop restoration plans for implementation in FY19	• Continue propagation efforts, including evaluation of 1st year restoration species • Continue restoration of RM -7L recreation area (primarily tamarisk removal and replant natives; 5-10 acres), • Monitor restored sites (Goals 1-4).
Year 3: Oct 1, 2019- Sept 30, 2020	• Continue propagation materials plans, testing and partnerships • Begin restoration activities and monitoring based upon the planning and consultation activities that occurred in FY18.	• Continue propagation efforts, including evaluation of previous 2 years efforts, • Restore Twelve Mile Bar (10-25 acres, primarily tamarisk); • Preparation/planning for restoration Ferry Swale area (10-30 acres; primarily tamarisk); • Monitor restored sites; develop Triennial Final Report with GRCA (Goals 1-4).

Budget: FY18 =$145,000 FY19 = $200,000 FY20 = $220,000

C.8. Evaluation of Means to Prevent Fish Passage through GCD

In the 2016 LTEMP EIS BO, Reclamation committed to evaluate means of preventing the passage of deleterious invasive nonnative fish through Glen Canyon Dam. Potential options to minimize or eliminate passage through the turbine or bypass intakes, or minimize survival of nonnative fish that pass through the dam would be assessed. While feasible options may not currently exist, technology may be developed later in the LTEMP period that could help achieve this goal.

This project would involve the gathering of information, documentation and evaluation of existing and emerging methods and technologies that may be considered for further feasibility analysis at a later date. The evaluation will include a review of existing technologies of entrainment and an evaluation of the success of current technologies at other facilities and their potential application to Glen Canyon Dam. This project may be implemented by Reclamation's Technical Services Division or an external contractor. On completion of the review, a next step may be to prepare a proposal for external funding from Reclamation's Science and Technology Program (S&T) that supports projects associated with managing water and generating power. This potential S&T research project is anticipated to fit within the S&T research categories of environmental issues and challenges associated with invasive species.

Products from this budget item include a white paper of the evaluation, a possible S&T project proposal and/or suggestions for future steps in the evaluation. This project supports Reclamation's compliance with the 2016 BO.

Budget: FY18 =$0 FY19 = $0 FY20 = $50,000

C.9. Evaluation of Temperature Control Methods at GCD

In the 2016 LTEMP EIS BO, Reclamation committed to explore the efficacy of a temperature control device, or methods, at Glen Canyon Dam to respond to potential extremes in hydrological conditions due to climate conditions that could result in nonnative fish establishment. This includes evaluations of current and evolving technological advances that could provide for warming and cooling the river in both high- and low-flow discharge scenarios, and high and low reservoir levels.

This project would involve the gathering of information, documentation and evaluation of existing and emerging methods and technologies that may be considered for further feasibility and risk analysis at a later date. This project with begin with a review of existing approaches that address temperature control methods particularly in the face of climate and hydrologic variability. This project may be implemented by Reclamation's Technical Services Division or an external contractor. The review would include an evaluation of the current technologies at other facilities and their potential application to Glen Canyon Dam. On completion of the review, a next step may be to prepare a proposal for external funding from Reclamation's Science and Technology Program (S&T) that supports projects associated with managing water and generating power. This potential S&T research project is anticipated to fit within the S&T research categories of environmental issues and challenges associated with invasive species, water quality and temperature variability as a result of climate and hydrologic variability.

Products from this budget item include a white paper of the evaluation, a possible S&T project proposal and/or suggestions for future steps in the evaluation. This project supports Reclamation's compliance with the 2016 BO.

Budget: FY18 =$50,000 FY19 = $0 FY20 = $0

C.10. Southwestern Willow Flycatcher and Yuma Ridgway's Rail Surveys

In the 2016 LTEMP EIS BO, Reclamation committed to monitoring the two endangered birds consulted on in the BO: the Yuma Ridgway's rail and the southwestern willow flycatcher. Reclamation will partially assist in funding National Park Service staff in conducting Yuma Ridgway's rail surveys once every three years and conduct southwestern willow flycatcher surveys once every two years for the duration of the LTEMP. The purpose of these surveys is to determine if potential habitat is occupied by breeding birds. These monitoring trips will be coordinated and combined with existing trips. Reporting and documentation will be provided to Reclamation by NPS staff certified to survey for nesting birds during the breeding season. Both birds would be surveyed in 2018, while only the Southwest willow flycatcher would be surveyed in 2020. The first budget cycle implementing this new conservation measure will focus on the presence/absence surveys in accordance with the conservations measures outlined in the BO. Future GCDAMP budget cycles may also consider research questions associated with these species.

Budget: FY18 =$17,000 FY19 = $0 FY20 = $10,000

Table 4. Reclamation Program Administration, ESA Compliance, and Management Actions Budget Summary

Fiscal Year 2018						
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
C	**Program Administration, ESA Compliance, and Management Actions**					**$ 949,000**
C.1	Administrative Support for NPS Permitting				$ 112,000	$ 112,000
C.2	Contract Administration	$ 75,000				$ 75,000
C.3	Integrated Stakeholder River Trip					$ -
C.4	Science Advisors Program				$ 150,000	$ 150,000
C.5	Experimental Management Fund				$ 400,000	$ 400,000
C.6	Native Fish Conservation Contingency Fund					$ -
C.7	Experimental Vegetation Treatment				$ 145,000	$ 145,000
C.8	Evaluation of means to prevent fish passage through GCD					$ -
C.9	Evaluation of temperature control methods at GCD				$ 50,000	$ 50,000
C.10	Ridgway's Rail and Southwest Willow Flycatcher monitoring				$ 17,000	$ 17,000
C	**Total Fiscal Year 2018**	**$ 75,000**	**$ -**	**$ -**	**$ 874,000**	**$ 949,000**

Fiscal Year 2019						
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
C	**Program Administration, ESA Compliance, and Management Actions**					**$ 984,370**
C.1	Administrative Support for NPS Permitting				$ 113,120	$ 113,120
C.2	Contract Administration	$ 75,750				$ 75,750
C.3	Integrated Stakeholder River Trip			$ 40,000		$ 40,000
C.4	Science Advisors Program				$ 151,500	$ 151,500
C.5	Experimental Management Fund				$ 404,000	$ 404,000
C.6	Native Fish Conservation Contingency Fund					$ -
C.7	Experimental Vegetation Treatment				$ 200,000	$ 200,000
C.8	Evaluation of means to prevent fish passage through GCD					$ -
C.9	Evaluation of temperature control methods at GCD					$ -
C.10	Ridgway's Rail and Southwest Willow Flycatcher monitoring					$ -
C	**Total Fiscal Year 2019**	**$ 75,750**	**$ -**	**$ 40,000**	**$ 868,620**	**$ 984,370**

Fiscal Year 2020						
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
C	**Program Administration, ESA Compliance, and Management Actions**					**$ 1,031,814**
C.1	Administrative Support for NPS Permitting				$ 114,251	$ 114,251
C.2	Contract Administration	$ 76,508				$ 76,508
C.3	Integrated Stakeholder River Trip					$ -
C.4	Science Advisors Program				$ 153,015	$ 153,015
C.5	Experimental Management Fund				$ 408,040	$ 408,040
C.6	Native Fish Conservation Contingency Fund					$ -
C.7	Experimental Vegetation Treatment				$ 220,000	$ 220,000
C.8	Evaluation of means to prevent fish passage through GCD				$ 50,000	$ 50,000
C.9	Evaluation of temperature control methods at GCD				$ -	$ -
C.10	Ridgway's Rail and Southwest Willow Flycatcher monitoring				$ 10,000	$ 10,000
C	**Total Fiscal Year 2020**	**$ 76,508**	**$ -**	**$ -**	**$ 955,306**	**$ 1,031,814**

D. NHPA Compliance and Cultural Resources Program Management

D.1. Cultural Resources Program Administrative Costs

This budget funds the salary and travel expenses of Reclamation cultural resources staff to administer the National Historic Preservation Act (NHPA) compliance for the GCDAMP utilizing the 2017 Programmatic Agreement (PA),which includes the Section 106 compliance, documentation for the Determination of Eligibility, contracting and reviewing of proposals and reports, annual cultural resources reporting and meeting, costs associated with maintaining the grants for tribal participation in the GCDAMP and tribal contracts to implement tribal monitoring protocols, general consultations, and Historic Preservation Plan development. This includes the implementation of the 2017 PA for Glen Canyon Dam Operations, as well as the 2012 Memoranda of Agreement (MOA) for Non-native Fish Control or its replacement. This budget item also supports Reclamation management involvement in tribal consultations and other cultural resources compliance activities.

The project goals and objectives are:

- 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 mitigation of at-risk historic properties and other related projects associated with implementation of NHPA compliance agreements for the operation of Glen Canyon Dam.
- Reclamation cultural resource personnel attending, as needed, TWG and AMWG meetings, Cultural Ad Hoc Group meetings, and conducting meetings required by the 2017 PA and revised 2012 MOAs.

Completion of this project’s components allow for compliance with the 2017 PA Stipulations I-IX, XI, and XII which also ensures accountability for the tribal grants and contracts and appropriate use of funds. The budget covers labor and travel for approximately 70% of one full time archeologist, as well as Reclamation management involvement in tribal consultations and other cultural resources compliance activities.

Budget: FY18 = $120,000 FY19 = $121,200 FY20 = $122,412

D.2. Support to Reclamation for Cultural Resources Compliance

Due to the workload involved in the implementation of the 2017 PA and limited Reclamation cultural resources staff, this budget item is for assistance with Reclamation's cultural resources compliance management. The awardee(s) will have expertise in drafting Historic Preservation Plans (HPP), will assist in the development of the HPP, and will support Reclamation's ongoing section 106 compliance activities carried out under the 2017 PA Stipulations. Reclamation's Regional Archeologist is responsible for the development of the HPP; however, the awardee(s) will assist greatly with the HPP development, including project management, coordination and/or writing sections of the HPP, document management, etc. Additional tasks for the awardee(s) include planning, coordinating and attending the annual PA implementation meetings, and drafting annual reports. Coordination with Reclamation's Regional Archeologist, the contracting officer, Tribes, GCMRC, and GCDAMP stakeholders and program manager is also expected. The awardee(s) may solicit GCDAMP expertise and input on cultural resources issues to support the fulfillment of these tasks. The two primary tasks are:

- Provide assistance to Reclamation for the administration and implementation of the GCDAMP cultural resources program, including assistance with Reclamation's compliance with Section 106 of the NHPA as defined in the 2017 PA. (FY18: $75,000, FY19: $40,000, FY20: $40,400)
- Assist with Reclamation's development of the HPP (FY18: $75,000, FY19: $0, FY20: $0)

Some of this funding may be used to support tribal participation (outside of formal consultation) in the development of the HPP, or other planning and compliance documents, where their unique expertise is necessary for adequately addressing issues, particularly associated with the management of their traditional cultural properties. Documentation of past Section 106 activities which includes a listing of all past monitoring and mitigation activities,for the HPP, is a priority The awardee will work cooperatively with GCMRC on Project D.4.

Completion of this Administrative support to Reclamation allows for compliance with the 2017 PA Stipulations I-IX, XI, and XII.

Budget: FY18 = $150,000 FY19 = $40,000 FY20 = $40,400

D.3. Cultural Resources Monitoring – Grand Canyon (NPS)

The NPS, Grand Canyon will conduct data review, field work within the CRE, data entry, analysis and report preparation to support Reclamation's Section 106 compliance and implementation of the 2017 LTEMP PA, Stipulations IV and VI. Field staff will utilize the existing 2016 Cultural Resource Management protocol and associated SOPs for all activities. Protocols will be used to streamline field activities. Additional data collection related to geospatial references and condition of archaeological sites will be gathered using a hardened field computer or hand-held unit and imported directly into the Cultural Resource geodatabase. The project goals and objectives are:

- Support Reclamation's Section 106 compliance responsibilities under the 2017 PA, Stipulations IV and VI
- Conduct field assessments to update condition and impact data using existing monitoring protocols and subsequent updates as defined in the Historic Preservation Plan (HPP)
- Provide Reclamation site data to support the development and implementation of the HPP
- Review and update site information and associated treatment recommendations contained within Reclamation's 2007 Geoarchaeological Investigations and Treatment Plan
- Coordinate with resource managers to design and implement appropriate management actions
- Streamline data collection and data management for cultural resources along the river corridor and report annually to Reclamation on activities and findings

Completion of this project component allows for compliance with the 2017 PA Stipulation VI, and NHPA, Section 106. The ultimate goal of the long-term monitoring program is to collect data to support the evaluation of impacts to historic properties (as identified in 2017 PA Stipulation VI & VII); and, as appropriate, to help identify mitigation measures to remediate sites damaged by the operations of Glen Canyon Dam.

Budget: FY18 = $47,000 FY19 = $48,000 FY20 = $48,000

D.4. Cultural Resources Monitoring – Glen Canyon (NPS)

Long-term monitoring of cultural resources within the CRE of the Glen Canyon Reach is required for compliance with Section 106 of NHPA and the Grand Canyon Protection Act, and implementation of the 2017 LTEMP PA, Stipulations IV and VI. Implementation of long-term monitoring in the Glen Canyon reach will be conducted by National Park Service (NPS) through Glen Canyon National Recreation Area (NRA) and coordinated with other NPS entities, Reclamation, the Grand Canyon Monitoring and Research Center (GCMRC), Tribes, and other stakeholders.

This project will maintain a program of long-term monitoring in the Glen Canyon reach that meets the updated requirements of the 2017 PA for LTEMP and the associated HPP. It will support the evaluation and documentation of effects to historic properties and inform the development of any mitigation measures identified to protect historic properties from documented adverse effects of dam operations. NPS would work with Reclamation to identify mitigation measures for any documented adverse effects at specific sites in Glen Canyon NRA. NPS will continue consultation concerning tribal values associated with Glen Canyon Reach with Hopi Tribe, Hualapai Tribe, Navajo Tribe, Southern Paiute Consortium, and Pueblo of Zuni. This consultation helps formulate a plan for ethnographic data collection to assist with mitigation of sites.

This project meets objectives of cultural resources protection on lands administered by Glen Canyon NRA using adaptive management processes for the NPS and Reclamation to achieve specific goals for identification, monitoring, documentation and mitigation actions with regard to cultural resources in the Glen Canyon reach during fiscal years 2018-2020. The project goals and objectives are:

- Support Reclamation's Section 106 compliance responsibilities under the 2017 PA, Stipulations IV and VI.
- Conduct field assessments to update condition and impact data using existing monitoring protocols and subsequent updates as defined in the Historic Preservation Plan (HPP).
- Provide Reclamation site data to support the development and implementation of the HPP.
- Conduct monitoring and data collection in support of evaluation of impacts to historic properties.
- Document effects to historic properties resulting from dam operations.
- Work with Reclamation to identify mitigation measures for any documented adverse effects at specific sites in Glen Canyon NRA.

Completion of this project component allows for compliance with the 2017 PA Stipulation VI. The ultimate goal of the long-term monitoring program is to monitor and document effects to historic properties in the Glen Canyon reach (as identified in 2017 PA Stipulation VI). The data will be useful for identifying mitigation measures to remediate any sites in the Glen Canyon reach damaged by the operations of Glen Canyon Dam.

Budget: FY18 = \$34,000 FY19 = \$25,000 FY20 = \$26,000

D.5. Traditional Cultural Property (TCP) Documentation for Hualapai, Navajo and Paiute Tribes

Reclamation has identified the need to document individual Tribal Traditional Cultural Properties (TCPs) in order to treat the TCPs as historic properties under 2017 PA, Stipulations I, IV, and VI . Under previous contracts, Reclamation initiated the documentation process with the five AMWG member tribes. The Hopi Tribe and the Pueblo of Zuni have completed TCP documentation. The Hualapai, Navajo and Paiute Tribes do not have documented TCPs. Future projects including Associative Values studies and possible projects related to Traditional Ecological Knowledge are based on TCP documentation. This project provides funding to assist in the documentation of TCPs for the Hualapai, Navajo and Paiute Tribes. The Pueblo of Zuni and the Hopi Tribe may require updates to their existing TCPs, as well. Funding from Tribal monitoring projects and the data and reports that result from this monitoring will also support the documentation of TCPs. This project will be closely coordinated with NPS efforts to document a single TCP for the entire canyon for all traditionally associated tribes. Funding for the NPS project will come from outside of the GCDAMP. It is anticipated that each tribe's documented TCP will be incorporated into the broader, canyon-wide multi-property TCP. The project goals and objectives are:

- Documentation of TCPs for Hualapai, Navajo and Paiute Tribes.
- Update documentation for Zuni and Hopi TCPs, as appropriate.

Completion of this project allows for compliance with the 2017 PA Stipulation I B(3) and IV A(7). The project product is the documentation of TCPs for the Hualapai, Navajo and Paiute tribes and possible updates to the TCPs for the Hopi Tribe and the Pueblo of Zuni. Funding for out years will be identified at a later date, if needed.

Budget: FY18 = $30,000 FY19 = $0 FY20 = $0

D.6. Tribal Associative Values Studies

Reclamation has identified that Tribal Associative Values Studies are part of a three step process. The first step is to identify the Associative Values for each Tribe. This step will be completed as part of Project D.5: TCP Documentation. Tribal Associative Values will be identified within the TCP documentation for future reference with respect to Historic Properties. The second step is to monitor and identify whether any Associative Values identified in the TCP documentation are being adversely affected by the operations of Glen Canyon Dam under the LTEMP. This monitoring will be completed as part of Project D.11: Tribal Cultural Resources Monitoring, the documentation of which is submitted to Reclamation in annual monitoring reports. In accordance with the 2017 PA, Stipulation I, if adverse effects are determined by Reclamation, the third step is the mitigation of the adverse effects.

When historic properties are valued for their association with important historical events and important people, mitigation may be accomplished by documenting those associations. An example of a past GCDAMP Associative Value project is the 2015 Zuni Associative Values study which mitigates for losses of Associative Values through the production of a film that documents the Zuni relationship to Grand Canyon.

The implementation of Tribal Associative Values studies (this project, D.6) under the 2017 PA, Stipulation I B, can be a stand-alone mitigation measure; or the results of the Associative Value study may identify future mitigation strategies for adverse effects to the character of historic properties as a result of the Glen Canyon Dam operations. Prior to beginning any tribal Associative Value study, it will be established whether the study itself is mitigation for the adverse effect or whether the study will identify future mitigation strategies. Associative Values

Studies are based on TCP documentation and the results of monitoring. Beginning in FY2019, Associative Values studies may be undertaken to mitigate or identify mitigation strategies for any tribe with a documented TCP and identified adverse effects to the character of historic properties as a result of the Glen Canyon Dam operations under the LTEMP. The steps associated with this project are:

1) Complete TCP documentation under project D.5. Identify and document historic properties and their associative values.

2) Continue monitoring of the TCPs and aspects of the associative values under project D.11 and under the GCPA. Document any effects as a result of the operations of Glen Canyon Dam under LTEMP.

3) Complete Associative Values studies as a method of mitigation or to offer mitigation strategies for any potential adverse effects that may be identified.

Completion of this project allows for compliance with the 2017 PA Stipulation I B(4), IV and VI. The ultimate goal is the mitigation of adverse effects to historic properties or to identify mitigation strategies for adverse effects. If these funds are not needed in a given year, they may be utilized for other 2017 PA compliance activities. Data sharing and cooperation with GCMRC Project J will occur if appropriate and in consultation with Tribes.

Budget: FY18 = $0 FY19 = $100,000 FY20 = $100,000

D.7. Cultural Sensitivity Training Development - Tribal Expertise

This project is to fund tribal expertise in the development of a GCDAMP cultural sensitivity training. Native American tribes possess special expertise in religious and cultural significance. It is recognized that this expertise is the outcome of extensive traditional learning and training that certain Native individuals go through to receive tribal recognition as an initiated individual, a medicine person, or a spiritual leader. Reclamation acknowledges and respects traditional knowledge and traditional education systems and recognizes that the inclusion of individuals with this knowledge is a vital component for the identification, evaluation, analysis, recording, treatment, monitoring or disposition of historic properties. Because not every researcher within the GCDAMP is able to undergo the intense training that certain Native individuals complete, this project will fund those experts to 1) assist the researchers to identify key aspects of religious and cultural significance; 2) develop training methods to pass this information on, and 3) to participate in the cultural sensitivity training.

This training will be developed and then revised on a recurring basis, as needed. Information from each of the five GCDAMP associated tribes will be incorporated into this training; the training will be developed by tribal members and lead by a project coordinator. The project coordinator’s role is to develop a written plan for the training, in coordination with representatives from each of the five GCDAMP associated tribes, and then to facilitate the implementation of the training. Funding in the FY18 will be for the project coordinator to develop a written plan for the cultural sensitivity training. Funding in FY19 and FY20 is intended for the development and implementation of the cultural sensitivity training, including coordination with the development of a video version of the training. If additional funds are deemed necessary for FY19 and FY20, the project coordinator will write a project proposal for the development and implementation of the cultural sensitivity training; additional funds may be reallocated to this budget item during the GCDAMP annual reassessment of the budget and work plan. Coordination with the development of HPP (under Reclamation project D.2) and the cultural sensitivity training video (Reclamation project D.9) will be required. The project goals and objectives are:

- Develop and implement a cultural sensitivity training program that will be used by all researchers working within the GCDAMP.

Completion of this project allows for compliance with the 2017 PA Stipulation IV A(9). The ultimate goal is to develop a training course for GCDAMP funded researchers and other interested GCDAMP participants. Additional sources of external funding will be explored and utilized, if appropriate.

Budget: FY18 = $10,000 FY19 = $15,000 FY20 = $15,000

D.8. Cultural Sensitivity Training Video

Following the development of the cultural sensitivity training identified in Reclamation project D.7, a video or on-line version of the training will be developed and circulated to allow the cultural sensitivity training to be more accessible for all GCDAMP researchers and stakeholders. This project includes the development of audio and visual elements of the training as well as other training materials. This project will be implemented by a contractor. Coordination with the project coordinator and tribal experts identified in Reclamation project D.7 is critical to the success of this project. The project goals and objectives are:

- Produce a Cultural Sensitivity Training video for use by all GCDAMP researchers and stakeholders

Completion of this project allows for compliance with the 2017 PA Stipulation IV A(9). The product is a video based on the Sensitivity Training developed in Reclamation project D.7 which will be a component of the Historic Preservation Plan under the PA.

Additional sources of external funding will be explored and utilized, if appropriate.

Budget: FY18 = $0 FY19 = $20,000 FY20 = $25,000

D.9. Hualapai Archive Project

The Hualapai archive project is to improve values and preserve stories of Hualapai tribal members in the Grand Canyon. For the past 30 years, the Hualapai Department of Cultural Resources (HDCR) has conducted interviews with Tribal Elders and Tribal Members to gain knowledge about resource condition and changes in resource health for resources in Grand Canyon. Some of these interviews were captured in hand written notes, some were associated with photographs about certain resources, some were audio recorded and some interviews were videotaped. Hundreds of interviews were conducted, and the information is stored in archival boxes at HDCR.

This collection of information needs to be organized and preserved for future generations by archiving this information into a digital database. The photographs and videos need to be converted to digital formats to preserve them before they deteriorate. One goal in creation of this database is to be able to query by resource or place and have all of the interviews (in all formats) that pertain to that resource/place be accessed. This database library will be able to be accessed by the community (for non-sensitive material) and will act as a data reference collection dedicated to preserving Hualapai heritage, language and culture. The project goals and objectives are:

- Produce a searchable digital database of photographs, notes, videos and audio recordings.

Completion of this project allows for compliance with the 2017 PA Stipulation I B for mitigation of potential adverse effects.

Budget: FY18 = $40,000 FY19 = $40,000 FY20 = $0

D.10. Contingency Fund for NHPA Section 106 Compliance

Compliance with the 2017 PA Stipulation I B for mitigation of potential adverse effects requires the mitigation of identified adverse effects to historic properties. Although no specific adverse effects or actions have been identified, this project is to set aside funding for possible future mitigation needs.

Reclamation's compliance with the 2017 PA Stipulation I B is the primary outcome of this project. The goal of this budget item is to ensure that funds are available to Reclamation in the event that 2017 PA Stipulation I B mitigation actions are required. Mitigation of documented adverse effects to historic properties due to operations of Glen Canyon dam under LTEMP during this budget cycle are eligible for use of these funds. Prior to utilization of these funds, Reclamation's Regional Archeologist will participate in an already planned river trip to assess and determine the level of mitigation necessary. Funds in this budget item will be accumulated over time, rolling from one year to the next, serving to ensure that funds are available for the mitigation actions should the need arise.

If funds allocated to the Experimental Management Fund (Reclamation project C.5) are not needed in a given year; at the end of the year, some of the funds may be allocated to the Contingency Fund for NHPA Section 106 Compliance. In 2018, if adequate funds are available, funds will be transferred with the goal of bringing the balance of the Contingency Fund for NHPA Section 106 Compliance up to a balance of $200,000 by the end of fiscal year 2018.

Budget: FY18 = $25,000 FY19 = $25,500 FY20 = $25,750

Carryover balance:

- End of FY17 carryover = $0
- End of FY18 anticipated carryover = $200,000
- End of FY19 anticipated carryover = $225,500

D.11. Tribal Resources Monitoring

This budget item provides funds to identify and monitor traditional cultural properties (TCPs) and to 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 Reclamation and the NPS to implement monitoring of historic properties in Glen and Grand Canyons.

The primary goal of this activity is to monitor and 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 Reclamation in compliance with the 2017 PA Stipulation VI.

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 Reclamation to assist in prioritization of historic properties for treatment in subsequent years. In addition, monitoring data will be used to update NPS databases.

This project includes funding for five tribes for up to $35,000 plus CPI each year.

Budget: FY17 = $175,000 FY18 = $176,750 FY20 = $178,518

D.12. Tribal Participation in the GCDAMP

This budget item provides funding through DOI agency appropriations (i.e., not power revenues) for the participation in GCDAMP meetings of the five GCDAMP Tribes (Hopi Tribe, Hualapai Tribe, Kaibab Paiute Tribe, Pueblo of Zuni, Navajo Nation). This funding covers preparation for meetings, participation in meetings, and travel costs associated with participation in the meetings. 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 (U.S. Geological Survey, National Park Service, Reclamation, U.S. Fish and Wildlife Service, and Bureau of Indian Affairs) provide appropriated funding to support this budget item, with Reclamation serving as lead agency for administration of these funds. This project is also a component of the tribal monitoring and referenced in the 2017 PA Stipulation VI.

Budget: FY18 = $475,000 FY19 = $475,000 FY20= $475,000

Table 5. Reclamation Cultural Resources Budget Summary

	Fiscal Year 2018					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
D	**Cultural Resources**					**$ 1,106,000**
D.1	Reclamation Cultural Resources Program Management	$ 120,000				$ 120,000
D.2	Support to Reclamation for cultural resources compliance				$ 150,000	$ 150,000
D.3	Cultural Resources Monitoring - Grand Canyon				$ 47,000	$ 47,000
D.4	Cultural Resources Monitoring - Glen Canyon				$ 34,000	$ 34,000
D.5	Documentation of Navajo, Hualapai, and Paiute TCPs				$ 30,000	$ 30,000
D.6	Associative values studies for TCPs					$ -
D.7	Cultural sensitivity training development - tribal expertise				$ 10,000	$ 10,000
D.8	Cultural sensitivity training video					$ -
D.9	Hualapai archive project				$ 40,000	$ 40,000
D.10	Contingency fund for NHPA section 106 compliance				$ 25,000	$ 25,000
D.11	Tribal cultural resources monitoring				$ 175,000	$ 175,000
D.12	**Tribal participation in AMP (not funded by power revenues)**				$ 475,000	$ 475,000
D	**Total Fiscal Year 2018**	**$ 120,000**	**$ -**	**$ -**	**$ 986,000**	**$ 1,106,000**

	Fiscal Year 2019					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
D	**Cultural Resources**					**$ 1,086,450**
D.1	Reclamation Cultural Resources Program Management	$ 121,200				$ 121,200
D.2	Support to Reclamation for cultural resources compliance				$ 40,000	$ 40,000
D.3	Cultural Resources Monitoring - Grand Canyon				$ 48,000	$ 48,000
D.4	Cultural Resources Monitoring - Glen Canyon				$ 25,000	$ 25,000
D.5	Documentation of Navajo, Hualapai, and Paiute TCPs				$ -	$ -
D.6	Associative values studies for TCPs				$ 100,000	$ 100,000
D.7	Cultural sensitivity training development - tribal expertise				$ 15,000	$ 15,000
D.8	Cultural sensitivity training video				$ 20,000	$ 20,000
D.9	Hualapai archive project				$ 40,000	$ 40,000
D.10	Contingency fund for NHPA section 106 compliance				$ 25,500	$ 25,500
D.11	Tribal cultural resources monitoring				$ 176,750	$ 176,750
D.12	**Tribal participation in AMP (not funded by power revenues)**				$ 475,000	$ 475,000
D	**Total Fiscal Year 2019**	**$ 121,200**	**$ -**	**$ -**	**$ 965,250**	**$ 1,086,450**

	Fiscal Year 2020					
	Project Description	**Reclamation Salaries**	**Travel**	**Operations / Supplies**	**Contracts / Cooperators**	**Total**
D	**Cultural Resources**					**$ 1,056,030**
D.1	Reclamation Cultural Resources Program Management	$ 122,412				$ 122,412
D.2	Support to Reclamation for cultural resources compliance				$ 40,400	$ 40,400
D.3	Cultural Resources Monitoring - Grand Canyon				$ 48,000	$ 48,000
D.4	Cultural Resources Monitoring - Glen Canyon				$ 26,000	$ 26,000
D.5	Documentation of Navajo, Hualapai, and Paiute TCPs					$ -
D.6	Associative values studies for TCPs				$ 100,000	$ 100,000
D.7	Cultural sensitivity training development - tribal expertise				$ 15,000	$ 15,000
D.8	Cultural sensitivity training video				$ 25,000	$ 25,000
D.9	Hualapai archive project					$ -
D.10	Contingency fund for NHPA section 106 compliance				$ 25,700	$ 25,700
D.11	Tribal cultural resources monitoring				$ 178,518	$ 178,518
D.12	**Tribal participation in AMP (not funded by power revenues)**				$ 475,000	$ 475,000
D	**Total Fiscal Year 2020**	**$ 122,412**	**$ -**	**$ -**	**$ 933,618**	**$ 1,056,030**

Table 6.1. Reclamation Total Budget Summary

			CPI	1%
Reclamation Adaptive Management Program Budget Summary FY2018-2020				
		2018	**2019**	**2020**
	GCDAMP Total (w/ 1% CPI)	**$ 11,025,454**	**$ 11,135,708**	**$ 11,247,066**
	Reclamation Total (20%)	$ 2,205,091	$ 2,227,142	$ 2,249,413
A	**Adaptive Management Work Group**	**$ 425,000**	**$ 428,750**	**$ 432,538**
	percent of BOR budget	**19%**	**19%**	**19%**
A.1	Adaptive Management Work Group Costs (BOR)	$ 220,000	$ 222,200	$ 224,422
A.2	AMWG Member Travel Reimbursement	$ 20,000	$ 20,200	$ 20,402
A.3	AMWG Reclamation Travel	$ 20,000	$ 20,200	$ 20,402
A.4	AMWG Facilitation Contract	$ 75,000	$ 75,750	$ 76,508
A.5	Public Outreach - Reclamation public affairs, POAG	$ 25,000	$ 25,250	$ 25,503
A.6	Public Outreach- Administrative History	$ 50,000	$ 50,000	$ 50,000
A.7	AMWG Other	$ 15,000	$ 15,150	$ 15,302
B	**Technical Working Group**	**$ 200,000**	**$ 202,000**	**$ 204,020**
	percent of BOR budget	**9%**	**9%**	**9%**
B.1	TWG Costs (BOR)	$ 120,000	$ 121,200	$ 122,412
B.2	TWG Member Travel Reimbursement	$ 25,000	$ 25,250	$ 25,503
B.3	TWG Reclamation Travel	$ 20,000	$ 20,200	$ 20,402
B.4	TWG Chair Reimbursement/Facilitation	$ 25,000	$ 25,250	$ 25,503
B.5	TWG Other	$ 10,000	$ 10,100	$ 10,201
C	**Program Admin, ESA Compliance, and Management Actions**	**$ 949,000**	**$ 984,370**	**$ 1,031,814**
	percent of BOR budget	**43%**	**44%**	**46%**
C.1	Administrative Support for NPS Permitting	$ 112,000	$ 113,120	$ 114,251
C.2	Contract Administration	$ 75,000	$ 75,750	$ 76,508
C.3	Integrated Stakeholder River Trip	$ -	$ 40,000	$ -
C.4	Science Advisors Program	$ 150,000	$ 151,500	$ 153,015
C.5	Experimental Management Fund	$ 400,000	$ 404,000	$ 408,040
C.6	Native Fish Conservation Contingency Fund	carryover from previous years		
C.7	Experimental Vegetation Treatment	$ 145,000	$ 200,000	$ 220,000
C.8	Evaluation of means to prevent fish passage through GCD	$ -		$ 50,000
C.9	Evaluation of temperature control methods at GCD	$ 50,000		
C.10	Ridgway Rail and Southwest Willow Flycatcher monitoring	$ 17,000	$ -	$ 10,000

Table 6.2. Reclamation Total Budget Summary

D	**Cultural Resources**	**$ 631,000**	**$ 611,450**	**$ 581,030**
	percent of BOR budget	**29%**	**27%**	**26%**
D.1	Reclamation Cultural Resources Program Management	$ 120,000	$ 121,200	$ 122,412
D.2	Support to Reclamation for cultural resources compliance	$ 150,000	$ 40,000	$ 40,400
D.3	Cultural Resources Monitoring - Grand Canyon	$ 47,000	$ 48,000	$ 48,000
D.4	Cultural Resources Monitoring - Glen Canyon	$ 34,000	$ 25,000	$ 26,000
D.5	Documentation of Navajo, Hualapai, and Paiute TCPs	$ 30,000	$ -	$ -
D.6	Associative values studies for TCPs	$ -	$ 100,000	$ 100,000
D.7	Cultural sensitivity training development - tribal expertise	$ 10,000	$ 15,000	$ 15,000
D.8	Cultural sensitivity training video	$ -	$ 20,000	$ 25,000
D.9	Hualapai archive project	$ 40,000	$ 40,000	$ -
D.10	Contingency fund for NHPA section 106 compliance	$ 25,000	$ 25,500	$ 25,700
D.11	Tribal cultural resources monitoring	$ 175,000	$ 176,750	$ 178,518
D.12	*Tribal participation in AMP (not funded by power revenues)*	*$ 475,000*	*$ 475,000*	*$ 475,000*
TOTAL Anctipated Available to Reclamation (w/ 1% CPI)		**$ 2,205,091**	**$ 2,227,142**	**$ 2,249,413**
TOTAL Reclamation Budget (Draft 2)		**$ 2,205,000**	**$ 2,226,570**	**$ 2,249,401**
	(Over) / Under budget	$ 91	$ 572	$ 12

Projects Funded Outside the GCDAMP

Reclamation supports projects and management actions outside of the GCDAMP in order to meet compliance obligations under the biological opinions for the 2007 Interim Guidelines and 2016 LTEMP EISs and to inform other Grand Canyon ecosystem goals. Findings and data from these projects are leveraged into GCDAMP research and monitoring. Reclamation supported projects outside the GCDAMP currently being implemented include:

Razorback sucker monitoring and research

Partners: BioWest / National Park Service / Reclamation / Northern Arizona University / GCMRC

In 2010, Reclamation's Upper Colorado Region and the Lower Colorado River Multi-Species Conservation Program (LCR MSCP) initiated a joint project to evaluate Razorback Sucker use of the Colorado River Inflow Area of Lake Mead (CRI). As a result of this study it was determined that razorback sucker were utilizing lower Grand Canyon and moving upstream into Grand Canyon. Additional sampling showed that humpback chub were also utilizing lower Grand Canyon. Reclamation will continue to fund BioWest and NPS to assist in continuing this small-bodied and larval fish monitoring of both species to determine their presence and distribution at different life stages, habitat use, and spawning of both species. Reclamation will coordinate with the GCRMC and GCDAMP on the results of the monitoring and research.

Reclamation is currently funding a Northern Arizona University graduate student in collaboration with GCMRC and AGFD to conduct a five year study to develop field identification tools for hybrid suckers, and evaluate sucker hybrid viability.

Brown trout control

Partner: National Park Service

The Brown Trout Control project is a continuation of funding provided to the NPS to implement comprehensive brown trout control activities in Bright Angel Creek and the Bright Angel Creek Inflow reach of the Colorado River. Additional actions may include brown trout control where new or expanded spawning populations develop, or other areas where trout control is determined to be necessary. This project will also support future planning efforts, including sonic-telemetry studies of habitat use and vulnerability to electrofishing for brown trout in Glen and Marble canyons.

Humpback chub translocations

Partner: National Park Service

Reclamation is funding NPS to implement humpback chub translocations into Colorado River tributaries. This requires removal of nonnatives and periodic monitoring. Currently translocations are successful in Havasu Creek and may be implemented in Shinumo and Bright Angel Creeks if they are determined viable. New actions include working in partnership with FWS, GCMRC, and most importantly, the Havasupai Tribe, to conduct preliminary surveys and a feasibility study for translocation of humpback chub into Upper Havasu Creek (above Beaver Falls). Other tributaries will also be assessed to determine their potential for additional translocations.

Lake Powell water quality monitoring

Partner: Reclamation Upper Colorado Region, Water Quality Group

Physical and biogeochemical processes in Lake Powell affect the nutrient concentration of dam releases. In the Colorado River Ecosystem temperature and nutrients affect trends in all aquatic resources as well as vegetation colonization on sandbars, and beach resources. Through its water quality group, Reclamation's Upper Colorado Region conducts water quality sampling in Lake Powell assisting the GCDAMP to better understand the effects of reservoir elevation, seasonal reservoir stratification and other factors that may be effecting the water quality of releases from the dam. See Appendix 1, Lake Powell Water Quality Monitoring, for more details.

Reservoir release temperature control methods

Partner: Reclamation, Science and Technology Program

Temperature control of reservoir releases is a high priority throughout Reclamation as it helps Reclamation to comply with biological opinions, water quality requirements, and supports the recovery of endangered fish species under the Endangered Species Act. There are currently several approaches in place at Reclamation dams to address temperature control; these include temperature control devices, temperature curtains, and reoperation strategies. Reclamation, through the Science and Technology program, is initiating a scoping-level project aimed to better understand the current state-of-the-practice on temperature control, identify needs and research gaps, develop partnerships, identify subject matter experts, and recommend future actions.

Table 7. Summary of Conservation Measures Activities

Consevation Measure		Activity that addresses it	Who is doing the work	Funding Source
Humpback Chub				
Translocations	Mainstem tributaries (Shinumo, Havasu Upper Havasu)	**NPS**-Humpback Chub Tributary Translocations and Associated Monitoring and Nonnative Fish Control; **GCMRC**-	NPS/GCMRC	AMP
	Chute falls	**GCMRC** - Project G	GCMRC/FWS	AMP
	Explore other tribs	**GCMRC**- Project G; **NPS** - Humpback Chub Tributary Translocations and Associated Monitoring and Nonnative Fish Control; **FWS** - coordination with Havasupai Tribe on translocations	GCMRC/NPS/FWS	AMP
	Nonnative removal in tribs	**NPS**-Humpback Chub Tributary Translocations and Associated Monitoring and Nonnative Fish Control	NPS/GCMRC	AMP
Mainstem	Expand aggregations outside	**GCMRC** Project G	GCMRC/FWS	AMP
	Mainstem augmentation	**GCMRC** Project G	GCMRC/FWS	AMP
LCR Monitoring	Spring and Fall Population estimates	**GCMRC** Project G	GCMRC/FWS	AMP
	LCR mainstem aggregation monitoring	**GCMRC** Project G	GCMRC/FWS	AMP
	Multistate model	**GCMRC** Project G	GCMRC	AMP
Mainstem monitoring	Aggregations	**GCMRC** Project G	GCMRC/NPS/FWS	AMP
	New populations & outside agregations	**GCMRC** Project G; **NPS/BioWest/FWS**	GCMRC/NPS/BioWest/ FWS	AMP/ Reclamation
	Parasite monitoring	**GCMRC** Project I	GCMRC	AMP
Refuge	Fund FWS Humpback Chub refuge (SNARRC)	**Reclamation**	FWS / Reclamation	Reclamation (outside AMP)
Razorback Sucker				
	Habitat use	**GCMRC**-Project F; **NPS/BioWest**-Razorback Sucker Monitoring and Adaptive Management, Larval and Small-bodied Fish	GCMRC/NPS/BioWest	AMP / Reclamation (outside AMP)
	Determine effects of dam operations-TMFs	**GCMRC**- Project H; **NPS**-Razorback Sucker Monitoring and Adaptive Management, Larval and Small-bodied Fish	NPS/GCMRC	AMP
	Determine extent of hybridization	Reclamation funded masters degree project	Reclamation	Reclamation (outside AMP)
Benefit Native Aquatic Species				
	Remove brown trout from Bright Angel, inflow & and other areas	**GCMRC**- Project F ; **NPS**-Humpback Chub Tributary Translocations and Associated Monitoring and Nonnative Fish	GCMRC/NPS	AMP
	Evaluate use of piscicide or other tools to renovate Bright Angel and Shinumo		NPS	
	Evaluate TMFs for brown trout	**GCMRC**-Project H	GCMRC	AMP
	Rapid Response	**GCMRC** - Project I; **NPS**-Invasive Species Monitoring & Management	NPS/GCMRC	AMP / NPS
	Evaluate temperature control methods	**Reclamation** Project C.9	Reclamation	AMP
	Evaluate means to prevent fish passage through the dam	**Reclamation** Project C.8	Reclamation	AMP
	Backwater slough	**NPS** - Invasive Species Monitoring and Management	NPS/Reclamation	NPS / Reclamation
Southwest Willow Flycatcher				
	monitor every 2 years	**Reclamation** Project C.10	NPS	AMP
Yuma Ridgway's Rail				
	monitor every 3 years	**Reclamation** Project C.10	NPS	AMP

Chapter 2. U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center Triennial Budget and Work Plan—Fiscal Years 2018–2020

Introduction

The Glen Canyon Dam Adaptive Management Program (GCDAMP) is an advisory process wherein protection, management, and improvement of Colorado River resources downstream from Glen Canyon Dam are considered in planning dam operations. The GCPA of 1992 directs the Secretary of the Interior (the Secretary) to establish and implement long-term monitoring and research 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 1995 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 (ROD) for the 1995 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. Recently, a new Long Term Experimental and Management Plan (LTEMP) EIS and ROD (U.S. Department of the Interior, 2016a) were completed that superseded the previous EIS and ROD. The 2016 final EIS and the December 15, 2016 ROD reaffirm continuation of the GCDAMP, AMWG and TWG and specify new experimental flow and no-flow actions and compliance requirements for the operations of Glen Canyon Dam during the next two decades.

The U.S. Geological Survey (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 2016 LTEMP ROD states that the GCMRC "will continue as one of the elements of GCDAMP, consistent with and for the purposes of the 1992 GCPA." Further, it states the GCMRC "will continue to function as a long-term monitoring and research center as was envisioned with its establishment in 1995 to provide scientific advice to GCDAMP, including the Secretary of the Interior, his/her designee, Department of Interior (DOI) managers, and AMWG."

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.

Approximately 80 percent of the GCDAMP annual budget supports the monitoring and research work of the GCMRC. The GCMRC is currently organized as a research station within the USGS Southwest Biological Science Center; however, the GCMRC was originally arranged 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 has increased with a corresponding shift to a staff comprised of more research scientists and fewer managers. This change has resulted in greater science productivity and allowed GCMRC to be responsive to the information needs of the GCDAMP through the development and implementation of several management plans including the 2011 HFE Protocol (U.S. Department of the Interior, 2011a), the 2011 Nonnative Fish Control EA (U.S. Department of the Interior, 2011b), and the LTEMP.

In fiscal years 2018, 2019, and 2020 (FY2018–20), the GCMRC and its cooperators will undertake monitoring and research activities that, in response to the legal requirements of GCPA and the recently approved LTEMP, will monitor the status and trends of natural, cultural, and recreational resources of the Colorado River between the forebay of Glen Canyon Dam and the western boundary of Grand Canyon National Park; this segment of the Colorado River is administratively termed the Colorado River ecosystem (CRe). In the LTEMP ROD, 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." All activities to be conducted by GCMRC in the CRe for FY2018-20 are described in this TWP.

Administrative History and Guidance That Informs This Work Plan

Each project described in the FY2018–20 TWP is organized around monitoring and research themes that are associated with the eleven resource goals identified in the LTEMP ROD: archaeological and cultural resources, natural processes, humpback chub, hydropower and energy, other native fish, recreational experience, sediment, tribal resources, rainbow trout fishery, nonnative invasive species, and riparian vegetation (U.S. Department of the Interior, 2016a; Attachment A). The monitoring and research projects are responsive to guidance provided in the LTEMP ROD, which, in addition to identifying the priority resources, also identifies flow and non-flow experimental actions and compliance obligations (see Compliance section below) for Glen Canyon Dam operations for the 20 years of the LTEMP. Additional guidance comes from the Science Plan developed by GCMRC (VanderKooi and others, 2017) in support of the LTEMP ROD which describes a general strategy for monitoring and research needed in support of implementation of operations and experimental actions.

In addition to the guidance from these documents, which is described in more detail later in this chapter, projects in this TWP have been informed by and build upon previous research and monitoring projects that were responsive to guidance vetted through the GCDAMP and the Secretary of Interior's office. While the LTEMP ROD defines broad resource goals and identifies new experimental actions and compliance requirements, some of the older guidance continues to have relevance for certain aspects of the current science program and continues to influence current research and monitoring directions in a general sense. Among this older guidance, the following documents describe the history of GCDAMP decisions and direction and help maintain continuity with GCDAMP goals as LTEMP is implemented:

- 2001 Glen Canyon Dam Adaptive Management Program draft strategic plan (Glen Canyon Dam Adaptive Management Program, 2001),
- 2007 Strategic Science Plan and Strategic Science Questions (SSQs) (U. S. Geological Survey, 2007),
- 2011 draft Core Monitoring Plan (U. S. Geological Survey, 2011), and
- 2012 AMWG Desired Future Conditions.

Monitoring and research themes described in these and other GCDAMP administrative documents have persisted throughout the life of the GCDAMP and are carried forward into the LTEMP. They include: (1) recovery of the endangered humpback chub (*Gila cypha*) and maintenance of populations of other native fish; (2) maintenance or improvement of the physical template, especially regarding fine sediment; (3) maintenance of culturally important sites, especially those that are of archaeological and historical significance under the National Historic Preservation Act (4) maintenance of the food base on which the native fish community depends; (5) maintenance of a high quality sport fishery in the Lees Ferry reach; and (6) maintenance of the native riparian vegetation community. The various goals, questions, information needs, and desired future conditions developed by GCDAMP committees also recognize the importance of maintaining high quality opportunities and conditions for recreational boaters and campers, and the role played by nonnative riparian vegetation in providing habitat for some desired fauna such as the endangered Southwestern willow flycatcher. In addition to these resource considerations, delivery of water, in accordance with the Law of the River including the 2007 Colorado River Interim Guidelines (U.S. Department of the Interior, 2007), 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 adaptive management process.

2001 Glen Canyon Dam Adaptive Management Program Draft Strategic Plan

Starting with the inception of the GCDAMP in 1997 and continuing over the course of several years (1997-2003), the AMWG worked on drafting a strategic plan to guide the adaptive management program into the future. As part of that effort, the AMWG and TWG defined 12 over-arching goals for the program (see p. 11, GCDAMP Strategic Plan; Glen Canyon Dam Adaptive Management Program, 2001) along with several specific management objectives for each goal. Numerous core monitoring information needs (CMINs), research information needs (RINs), and effects (of experiments) monitoring information needs (EMINs) were also identified for each of the goals. Although comprehensive in scope, the resulting strategic plan was never formally approved, in part because AMWG members could not reach final agreement about certain details of the plan such as where to draw the line in terms of defining what was within or outside the scope of the program and how to prioritize research and monitoring activities.
In August 2004, AMWG members participated in a workshop focused on prioritizing topics to guide future research and monitoring activities. The outcome of this workshop was the identification of the following five priority issues or topics, framed as questions:

1) Why are the humpback chub not thriving, and what can we do about it? How many humpback chub are there and how are they doing?
2) Which cultural resources, including Traditional Cultural Properties (TCPs), are within the Area of Potential Effect, which should we treat, and how do we best protect them? What is the status and trends of cultural resources and what are the agents of deterioration?
3) What is the best flow regime?
4) What is the impact of sediment loss and what should we do about it?
5) What will happen when we test or implement the Temperature Control Device (TCD)? How should it be operated? Are safeguards needed for management?

Although these priority questions were subsequently superseded by later guidance from DOI, many of these issues continue to be high priorities. This is demonstrated by funding allocations to humpback chub research and monitoring and related topics such as food base and non-native species, sediment monitoring and research, and cultural resource management in this work plan.

2007 Strategic Science Plan and Strategic Science Questions

In 2005–06, GCMRC began developing a series of strategic planning documents to guide the science activities of the GCDAMP over the next five years, starting first with a 5-year strategic science plan that explicitly addressed the priority management questions identified in the August 2004 AMWG workshop mentioned previously. The Strategic Science Plan (SSP) identified a suite of strategic science questions (SSQs) that had emerged from a 2005 Knowledge Assessment Workshop and were linked to the five priority issues identified by AMWG in 2004. Because of the inherent complexity of the Colorado River ecosystem and the logistical challenges involved with studying its various components, many of the SSQs identified in the final 2007 SSP remain relevant to the research and monitoring programs identified in the FY2018-20 work plan. These include questions related to determining the drivers of native and nonnative fish population dynamics and the aquatic foodbase, understanding the effects of dam operations on cultural resources, riparian vegetation, aquatic organisms, and sediment, and identifying and evaluating experimental actions to manage sediment, water quality, and native and nonnative fish.

2011 Draft General Core Monitoring Plan

A final draft General Core Monitoring Plan (CMP) was developed by GCMRC for TWG review in February 2011. Although only the first step of an anticipated 4-step process, the 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 department-level policy actions 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.

Core monitoring is "consistent, long-term, repeated measurements using scientifically accepted protocols to measure status and trends of key resources … potentially affected by Glen Canyon Dam 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 AMWG and a 2005 TWG Science Planning Group. At the time of completion of the CMP, the TWG requested GCMRC to develop individual draft core monitoring plans responsive to each of the 12 Adaptive Management Program goals (see p. 11, GCDAMP Strategic Plan; Glen Canyon Dam Adaptive Management Program, 2001), 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. The monitoring activities proposed in the FY2018–20 TWP represent GCMRC's best professional judgment concerning how best to collect critical data about resource condition and ecosystem processes for those resources that have been identified as being of highest priority in the LTEMP ROD.

The CMP recognized that monitoring should be pursued within an ecosystem context. Although the CMP was organized around the original 12 GCDAMP goals, it distinguished between ecosystem resources and ecosystem drivers. Ecosystem resources were native and non-native fish, extirpated species, Kanab ambersnail, spring and riparian habitats, recreational resources, cultural resources, and hydropower. Ecosystem drivers were stream flow, water quality (including nutrients), sediment transport and sediment supply, and the aquatic and terrestrial food web.

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 measurable targets for each resource category 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 also 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.

The CMP provides an in-depth administrative history of monitoring programs since the inception of the Glen Canyon Ecosystem Studies program in the 1980s 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 previous 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 began development of the series of science planning documents, the last of which was the CMP.

In developing the FY2018-20 TWP, GCMRC has worked with sister agencies and collaborators to develop efficient monitoring 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 core monitoring protocols will be to take the advancements described in this latest TWP and incorporate these into a revised General CMP.

2012 AMWG Desired Future Conditions

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) and initially adopted by the AMWG as a draft in August 2011. The DFCs were then revised, reconsidered, and formally adopted by the AMWG in February 2012. The DFCs were partly derived from 12 goals identified in the 2003 GCDAMP draft Strategic Plan and 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. In response, GCMRC used these DFCs in the development of the preceding FY2015–17 TWP.

In many cases, the DFCs reflected contrasting visions of the CRe. For example, 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. Also, 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 current fish management policy is to a large extent grounded on and dependent on the substantial monitoring and research program described in this TWP. 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. 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 past work plans and the FY2018–20 TWP. Past scientific activities and those be undertaken in FY2018–20 seek to describe and quantify the complex interactions among pre-dam relict and post-dam artifact resources (e.g., sandbars) 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 resource goals that helped define the scope of GCMRC’s past activities. Moving forward, the 11 succinct resource goals defined in LTEMP ROD (see below) that were derived in part from the DFCs, are now the primary resource goals of the GCDAMP. The LTEMP goals deviate from the DFCs by not including a goal specific to extirpated species and by adding goals specific to natural processes and tribal resources.

Although the DFCs have been superseded by LTEMP goals, they continue to provide guidance to the GCDAMP in a supplementary role to the LTEMP ROD.

2016 LTEMP ROD

The most recent and important guidance for developing the current TWP is provided in the LTEMP ROD, which was signed by then Secretary Jewell on December 15, 2016 (U.S. Department of the Interior, 2016). In the ROD, the Secretary confirmed the selection of Alternative D from the FEIS as the new LTEMP, noting that this plan provides “a framework for adaptively managing Glen Canyon Dam operations and other management and experimental actions over the next 20 years, consistent with the GCPA and other requirement of federal law.” The ROD specified 11 broad resource goals for improving resource conditions under the LTEMP (Table 1). Most of these goals have clear linkages to past guidance documents like the 2001 GCDAMP Strategic Plan (Table 1). These linkages provide continuity for the GCDAMP between past planning efforts and current guidance provided in the LTEMP ROD.

The LTEMP includes several experimental flow and non-flow actions that will be carried out as conditions warrant during the 20-year time frame of the plan. These include several types of high-flow experiments (HFEs), trout management flows, macroinvertebrate production flows, low summer flows, actions to benefit humpback chub (e.g., translocations, nonnative fish removals), and non-flow vegetation treatments (see Table 4 of Attachment B, LTEMP ROD; U.S. Department of the Interior, 2016). In addition, the LTEMP ROD and its associated Biological Opinion (BiOp; Department of the Interior, 2016b) list numerous compliance actions that must be implemented to meet environmental commitments, many of which incorporate scientific research or monitoring components or rely on outcomes of research and monitoring activities. These environmental commitments include conservation measures to benefit or promote the recovery of humpback chub, razorback sucker (*Xyrauchen texanus*), and Kanab ambersnail (*Oxyloma haydeni kanabense*).

2017 LTEMP Science Plan

The LTEMP Science Plan developed by GCMRC (VanderKooi and others, 2017) provides a description of the collection and analysis of scientific data relevant to the implementation of the LTEMP ROD. Specifically, this plan describes a general strategy by which monitoring and research will be conducted by GCMRC and its cooperators with results provided to the DOI, its bureaus, and to the GCDAMP between 2017 and 2037. Given the 20-year duration of the LTEMP, the science plan will need to be reviewed and potentially updated on a periodic basis.

Table 1. Resource goals for the Long-Term Experimental and Management Plan (LTEMP) cross walked to the goals of the 2001 Glen Canyon Dam Adaptive Management Program (GCDAMP) Strategic Plan.

LTEMP Resource Goals	GCDAMP Goals (2001 GCDAMP Strategic Plan)
1) Archaeological and Cultural Resources Maintain the integrity of potentially affected NRHP-eligible or listed historic properties in place, where possible, with preservation methods employed on a site-specific basis.	***Goal 11.*** Preserve, protect, manage and treat cultural resources for the inspiration and benefit of past, present and future generations.
2) Natural Processes Restore, to the extent practicable, ecological patterns and processes within their range of natural variability, including the natural abundance, diversity, and genetic and ecological integrity of the plant and animal species native to those ecosystems.	***Goal 7.*** Establish water temperature, quality and flow dynamics to achieve GCDAMP ecosystem goals. ***Goal 1*** . Protect or improve the aquatic foodbase so that it will support viable populations of desired species at higher trophic levels. ***Goal 5.*** Maintain or attain viable populations of Kanab ambersnail. ***Goal 3*** . Restore populations of extirpated species, as feasible and advisable.
3) Humpback Chub Meet humpback chub recovery goals, including maintaining a self-sustaining population, spawning habitat, and aggregations in the Colorado River and its tributaries below the Glen Canyon Dam.	***Goal 2*** . Maintain or attain viable populations of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats.
4) Hydropower and Energy Maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources.	***Goal 10.*** Maintain power production capacity and energy generation, and increase where feasible and advisable, within the framework of GCDAMP ecosystem goals.
5) Other Native Fish Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.	***Goal 2.*** Maintain or attain viable populations of existing native fish, remove jeopardy for humpback chub and razorback sucker, and prevent adverse modification to their critical habitats.
6) Recreational Experience Maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.	***Goal 9.*** Maintain or improve the quality of recreational experiences for users of the Colorado River ecosystem, within the framework of GCDAMP ecosystem goals.
7) Sediment Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.	***Goal 8.*** Maintain or attain levels of sediment storage within the main channel and along shorelines to achieve GCDAMP ecosystem goals.
8) Tribal Resources Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons	***Goal 11*** . Preserve, protect, manage and treat cultural resources for the inspiration and benefit of past, present and future generations.
9) Rainbow Trout Fishery Achieve a healthy high-quality recreational rainbow trout fishery in GCNRA and reduce or eliminate downstream trout migration consistent with NPS fish management and ESA compliance.	***Goal 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.
10) Nonnative Invasive Species Minimize or reduce the presence and expansion of aquatic nonnative invasive species.	
11) Riparian Vegetation Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.	***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.
	Goal 12. Maintain a high quality monitoring, research, and adaptive management program.

The science plan is structured around routine monitoring activities as well as flow and non-flow experiments identified in the LTEMP ROD. Included are activities to monitor specific resource conditions necessary to trigger experimental actions as well as temporarily suspend or permanently end experimental actions determined to have unacceptable adverse effects on key resources. The resources specifically identified in the LTEMP ROD to be evaluated are 1) water quality and water delivery, 2) humpback chub, 3) sediment, 4) riparian ecosystems, 5) historic properties and traditional cultural properties, 6) Tribal concerns, 7) hydropower production and the Upper Colorado River Basin Fund (see https://www.usbr.gov/uc/rm/crsp/bf.html), 8) the rainbow trout fishery, 9) recreation, and 10) other resources. The FY2018-20 TWP focuses on implementing monitoring and research activities that will provide information on the status and trends in resource conditions which will complement and support future implementation of experiments and operational decisions during the next three-year window of the LTEMP ROD.

The goals of the science activities conducted by the GCMRC in the FY2018-20 TWP are to inform operational decisions and resource objectives that are described in the LTEMP ROD. In addition, the work of the GCMRC and its cooperators will address scientific uncertainties, monitor resource trends that are affected entirely, or in part, by dam operations, and meet conservation measures and other compliance obligations. The specific activities included in each work plan will be reviewed and recommended by the TWG and AMWG and ultimately approved by the Secretary of the Interior.

Development of FY2018-20 Work Plan – Timeline and Feedback

Development of this TWP began in late January 2017 when the GCMRC convened an annual reporting meeting. This meeting was immediately followed by a TWG meeting during which the monitoring and research 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. Throughout early 2017, ad hoc groups of the TWG and interagency/cooperator meetings were held to solicit monitoring and research recommendations from stakeholders. For example, the Socio-Economic Ad Hoc Group (SEAHG) made recommendations for projects to be conducted in FY2018–20 that address socioeconomic concerns expressed in the LTEMP; TWP Project J is responsive to those recommendations.

Concurrent with the initial planning phase, the TWG completed a Knowledge Assessment exercise to ascertain stakeholder perceptions of where the program currently stands relative to understanding drivers and factors influencing resource conditions in the CRe. Teams composed of different combinations of stakeholders, GCMRC scientists, and cooperating agency staff and scientists produced assessments for each resource category identified in LTEMP, except for tribal resources. This exercise helped to highlight areas where information is relatively complete as well as knowledge gaps and areas of uncertainty. A report to the TWG on the results of this

Knowledge Assessment was produced by the Science Advisors Program which helped inform the development of this work plan.

Thereafter, the GCMRC received direct input from numerous stakeholders, met in-person with Tribal representatives on three separate occasions, and had a series of conference calls with the Budget Ad Hoc Group (BAHG) in March. Various TWG members provided direction and suggestions on research and monitoring activities to be included in the TWP. In some cases, suggestions were large-scale and concerned the geographic scope of GCMRC's investigations or the need to modify experimental work. Other suggestions were more detailed in nature. In other cases, BAHG suggestions were directed at Reclamation's portion of the budget that is described in Chapter 1 of this TWP. While it was not possible to directly address every suggestion received due to budget limitations, policy direction, or conflicting management objectives, GCMRC considered all comments and suggestions and engaged in an open and transparent discussion with stakeholders, Tribal representatives, and the BAHG over the course of developing the TWP. The timely nature of the first round of input – prior to development of the first draft of the FY 2018-20 TWP – ensured that many suggestions were incorporated in the first draft sent to the TWG in early April 2017.

Discussions among the GCMRC staff, GCDAMP stakeholders, agency staff, and cooperators continued at the April TWG meeting. At this meeting, the TWG formally provided feedback on the proposed outline of the TWP and extended abstracts of proposed research and monitoring projects. In most cases, the TWG was supportive of the project ideas developed by GCMRC staff and cooperators. More detail was requested in a variety of areas including proposed methods, sampling design, and study objectives. Based on this input, the GCMRC project Principal Investigators (PIs) and cooperators developed detailed project proposals that included lists of investigators, project summaries, background information, descriptions of proposed work, expected products to result from the project, references, and detailed budgets. Summary budget tables for the entire TWP were also prepared. The project descriptions and budgets along with a brief introduction were compiled into a full draft of the FY2018-20 TWP which was submitted in mid-May 2017 to Reclamation and also the Science Advisors Program for their formal review. It was recognized in the Introduction to the May draft of the TWP that proposed annual budgets, by project, exceeded anticipated funding by margins of 19-31 % and that additional sources of funding had yet to be identified. The suspension of Federal Advisory Committee Act (FACA) activities per the May 5, 2017 Department of Interior memo precluded review of this draft by the TWG, BAHG, and other stakeholders

The Science Advisor's review of the May 2017 draft TWP was received by GCMRC on June 9, 2017. Principal Investigators began revising project narratives in response to this review in order to complete a third draft of the TWP by the end of June 2017. In response to the FACA suspension, Reclamation applied for, and subsequently obtained, a partial waiver from this order. The waiver allowed meetings of AMWG subcommittees to resume such that the TWP planning process could continue during the FACA committee review. The resumption of subcommittee activities allowed GCMRC to submit the June 30, 2017 draft of the TWP to not only Reclamation, but also the TWG and BAHG for their review. GCMRC also developed a formal Response to the Science Advisor's review that was shared with the TWG in August and serves as a companion document to the TWP.

The June 2017 TWP included the same components as the May draft and also identified funding sources for all proposed work. In order to reconcile the total budget presented in the May 2017 draft with anticipated funding levels, the GCMRC Chief directed PIs to reduce their budgets according to the priorities, resource goals, and environmental commitments under LTEMP ROD criteria outlined in the introduction to the May 2017 draft. Specifically, GCMRC investigators were directed to prioritize projects and elements focusing first on LTEMP implementation. Criteria included whether or not the proposed work was necessary to trigger an experiment, for monitoring an ecosystem response, to inform experimental off-ramps, or for context in interpreting responses to experiments. Compliance with the BiOp and National Historic Preservation Act were also priorities. Next level criteria included whether or not the proposed work was: duplicative; at the appropriate level of effort; included tribal coordination as appropriate; was efficient logistically; and was of high quality. Feedback received from stakeholders and others during previously mentioned interactions provided helpful guidance for identifying areas for budget reductions. GCMRC leadership then ranked all project elements as high, medium, or low priority based on their interpretation of these same criteria and eliminated funding for all lower priority elements. They then cut funding levels to remaining project elements by reducing tasks, field activities, and staffing levels in order to reach an overall budget near projected funding levels. Those elements or portions of elements that were not funded in the June 2017 draft are included at the end of each project such that it is clear what changes were made from the May 2017 draft. The final steps at balancing the budget included using projected FY2017 carryover funds to provide the first annual installment for the FY2020 overflight (see Project L) and proposing to use the Native Fish Conservation Contingency Fund in FY2019 and FY2020 to ensure all activities identified as conservation measures in the BiOp will be conducted.

After submission of the June 2017 draft of the TWP, the BAHG conducted a series of conference calls with GCMRC staff in July and early August. The objective of these meetings was for stakeholders to discuss and ask questions about individual projects and the overall TWP and to provide feedback to GCMRC regarding the final draft of the FY2018-20 TWP. In addition to the verbal comments made by BAHG members during these calls, written comments and suggested revisions to projects were also provided to GCMRC in the form of a list of eight general consensus comments from the BAHG and specific comments from some stakeholders. As with comments and suggestions received from stakeholders and other reviewers on previous drafts of the TWP, GCMRC took this feedback into consideration as PIs worked to revise projects and other components of the TWP into the August draft presented to the TWG for their consideration.

The TWG met in late August to discuss the revised draft of the TWP and to develop a motion to recommend that AMWG recommend for approval the FY2018-20 TWP to the Secretary of Interior. The motion that was approved by a majority vote of TWG members present at the meeting included a list of 10 changes to the TWP, four for Reclamation projects and six for GCMRC projects. For GCMRC projects, these included eliminating elements from Project D, adding back research elements to Project E, and restoring several fish monitoring trips to Projects G and I. In addition, the lack of emphasis on the Hydropower LTEMP Resource Goal was noted and addressed by adding work to Project J and creating Project N. Based on the language in the approved motion, Reclamation and GCMRC developed this final draft of the FY2018-20 TWP for consideration by the AMWG. This draft incorporates all the changes from the TWG motion for GCMRC projects with one exception. Project element D.1 was retained in order to meet GCMRC's obligation to provide relevant scientific information in support of the Archaeological and Cultural Resources LTEMP Resource Goal.

Budget allocations

In most cases, GCMRC staff had lead responsibility to develop each project, and each PI collaborated with staff of sister agencies, university and private sector cooperators, and others to review the state of knowledge regarding monitoring protocols and to identify critical scientific uncertainties. Projects were primarily organized around resource categories that were identified in the LTEMP ROD and tribal resource-related concerns are addressed within specific resource categories such as aquatic food base and humpback chub. Several projects identified monitoring activities that would only occur in the event that condition-dependent experiments are triggered. Descriptions of these activities and associated budgets are included in the respective projects, but as separate project elements and budget tables. Funding for these contingencies is proposed to come from the experimental fund as described in Chapter 1.

As noted above, the May draft budget was significantly higher than could be supported by available funding while the June, August and September drafts each presented a work plan consistent with anticipated funding availability. To fully fund all activities described in this work plan, carryover funding from FY2017 and allocations from Reclamation's Native Fish Conservation Contingency Fund, as described in Chapter 1, will be required. Several elements in Project G, Humpback Chub Population Dynamics throughout the Colorado River Ecosystem, will be funded in FY2019 and FY2020 by reallocation of money from this fund. Funding levels in the Native Fish Conservation Contingency Fund are projected to be approximately $1.4 million at the beginning of FY2018 and as much as $1.8 million at the beginning of FY2019. The latter amount is sufficient to conduct eight to ten non-native fish control trips per year for up to two years if they are deemed necessary. We note that mechanical removal of nonnative fishes can only occur if the Tier 2 trigger in the LTEMP BiOp is reached. This trigger occurs when adult humpback chub population estimates are less than 7,000 individuals. Population trends for adult humpback chub have been stable for many years, although there is considerable uncertainty associated with the abundance estimates. Given long-term survival rates of adult humpback chub, it is highly unlikely that Tier 2 triggers will be reached during FY2018-20. Since mechanical removal of nonnative fish is unlikely to be required, our proposed use of the Native Fish Conservation Contingency Fund is reasonable.

Of particular note in the budget is the work funded under Appendix 1. Reclamation has provided independent funding for research and monitoring of Lake Powell water quality through approximately June 2019. However, there is no commitment of additional funding beyond that date. The work described in Appendix 1 provides important support to the work elements described in Project E, which is focused on defining fundamental drivers of the aquatic ecosystem in the CRe. Therefore, identifying funding to extend data collection, modeling, and analysis work in Appendix 1 beyond June 2019 is a priority.

Overhead rates for GCDAMP funds expended by GCMRC are projected to increase from the current rate of 12% to 15.557% in FY2018 and 26% in FY2019 and FY2020. The rate for funds transferred to cooperating agencies will remain 3%. The increases listed above are due to expected higher facility costs associated with a new building. New facilities are required since the City of Flagstaff, from whom USGS leases space, has determined that GCMRC's current building has outlived its useful lifespan and must be demolished. Although delayed for several years, current projections are to move into this yet to be built facility in summer 2018. The increases in overhead rates will result in less funding available for science activities. Despite this, the USGS is required by law to recover full costs associated with conducting reimbursable work. Overhead rates are calculated by GCMRC's parent organization, the Southwest Biological Science Center (SBSC), and varies year to year depending on funding levels (reimbursable and appropriated) and Center costs (lease costs, supplies, SBSC administrative staff, etc.). With approvals, USGS allows reduced overhead rates to be charged as is done for funding from the GCDAMP. In those cases, SBSC is required to make up the difference between funding generated from that reduced rate and actual costs with appropriated funds (known as "cost-share" by USGS). To cover this cost-share in support of GCMRC's work for the GCDAMP, the USGS contributes approximately $1,000,000 in appropriated funds per year to SBSC. We note that this funding is not a certainty and periodically SBSC is required to submit justifications to USGS leadership for this continued support. The most recent justification was required in August 2016. Were this cost-share funding to decrease or be eliminated, GCMRC would be forced to charge higher overhead rates for GCDAMP funding and thus further reduce the amount of money available for science.

FY2018-20 Work Plan Relative to LTEMP Resource Goals, Experimental Actions, and Compliance Obligations

The monitoring and research studies identified in the FY2018–20 TWP are intended to address priority resources, flow and non-flow experimental actions, and compliance obligations for future operations of the Glen Canyon Dam under the LTEMP ROD. This section describes the relations between major LTEMP resource, monitoring, and research themes and each project. The project elements that support different LTEMP experimental actions and resource goals are summarized in Table 2.

Table 2. Project elements in the FY 2018-20 Triennial Work Plan that address some aspect of the Long-Term Experimental and Management Plan (LTEMP) Resource Goals relative to LTEMP dam operations and experimental actions. Gray boxes indicate no relevance.

LTEMP General Dam Operations & Experimental Actions / LTEMP Resource Goal	Archeological and cultural resources	Natural Processes	Humpback chub	Hydropower and energy	Other native fish	Recreational experience	Sediment	Tribal resources	Rainbow trout fishery	Nonnative invasive species	Riparian vegetation
General dam operations	D.1/D.2	A.1/A.2 C.1/C.2 E.1/E.2 F.1/F.3/F.4 Appendix 1	E.1/E.2 F.2 G.1/G.2/G.3/ G.4/G.5/G.6/G.9 I.1/J.2	N.1	E.1/E.2 F.2 G.9 I.1	B.1/B.2/B.4 H.1	A.1/A.3 B.1/B.2	J.1	E.1/E.2 F.4 G.9 H.4 I.1	F.5 I.1/I.2/I.3 G.9 J.2	C.1/C.2
Fall High Flow Experiments (HFE) > 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Fall HFE ≤ 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Humpback chub translocation			G.1/G.7/G.8							G.7/G.8	
Larval humpback chub head-start program			G.1								
Macroinvertebrate production flows		F.3	F.1/F.2/F.4	N.1	F.1/F.2/F.4				F.1/F.4 H.1/H.2/H.3	I.1	
Mechanical removal of invasive fish			I.1/I.2							I.1	
Mechanical removal of rainbow trout from LCR reach			I.1/J.2		I.2					J.2	
Proactive spring HFE ≤ 45,000 ft³/s, in April, May or June	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Riparian vegetation restoration	D.1	C.3/C.4				C.3/C.4				C.3/C.4	C.1/C.2/C.3/C.4
Spring HFE ≤ 45,000 ft³/s, in March or April	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Trout management flows		C.1/C.2/C.3	J.2	J.2 N.1					H.1/H.2/H.3	F.5 J.2	C.1/C.2/C.3

Stream Flow, Water Quality, Sediment Transport and Budgeting, and Sand Bar Monitoring and Storage

This theme includes all work performed under Projects A, B, and components of work performed in Project E and Appendix 1. Project A provides the primary linkage between Glen Canyon Dam operations and the physical and chemical characteristics of the CRe by collecting and interpreting the basic measurements of stage, discharge, water quality, and sediment transport at various locations. The data collected by this project are used to implement the HFE Protocol, to evaluate the reach-scale sand mass-balance response to the HFE Protocol, and to evaluate the downstream effects of releases conducted under the LTEMP. Project B tracks the effects of individual HFEs on sandbars, monitors the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and investigates the interactions between dam operations, sand transport, and eddy sandbar dynamics. Project E and Appendix 1 intend to better constrain the important drivers of nutrient outflow from Glen Canyon Dam and to capitalize and expand upon a large volume of historical nutrient data that has been collected in Lake Powell.

The projects in this theme directly evaluate progress towards achieving **LTEMP Resource Goal 7** (Sediment) by providing information on flows, sediment flux, and sandbar size and volume in the Colorado River downstream of Glen Canyon Dam (Table 2). They also provide support towards achieving **LTEMP Resource Goals 1, 2, 3, 5 and 9** (Archeological and Cultural Resources, Natural Processes, Humpback Chub, Other Native Fish, and Rainbow Trout Fishery) by collecting the stage, flow, and sediment data used to assess effects of dam operations on cultural sites and by providing water-quality data used for the assessment of fish growth rates, population models, and habitat changes for native and non-native fish. Finally, these projects support **LTEMP Resource Goals 6 and 11** (Recreational Experience and Riparian Vegetation) 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 and as substrates for riparian vegetation and marsh communities (Table 2).

Terrestrial Ecosystems: Riparian Vegetation, Geomorphic Effects on Archeological Sites, and Remote Sensing Overflight

This theme includes all work performed under Projects C, D, and L. Project C provides key monitoring data on riparian vegetation and its response to dam operations. These data are used to determine if the LTEMP Resource Goals for riparian vegetation are being met, if the data can be used to address gaps related to predicting the responses of vegetation to LTEMP experimental flows, and if the implementation of experimental vegetation treatments supports their goals. Project D quantifies the geomorphic effects of ongoing and experimental dam operations, as well as the geomorphic effects of riparian vegetation expansion and management, focusing on effects to the supply of sediment to cultural sites and terraces. Project L collects system-wide, high-resolution multispectral imagery and a Digital Surface Model (DSM) of the Colorado River corridor from the forebay of Glen Canyon Dam downstream to Lake Mead, and along major tributaries to the Colorado River. The data sets derived from previous remote sensing overflights have proven to be extremely valuable to many of the research projects conducted by GCMRC.

The projects in this theme directly evaluate progress towards achieving **LTEMP Resource Goals 1 and 2** (Archeological and Cultural Resources and Natural Processes) by providing information on status and trends in the physical conditions associated with archeological and cultural sites including vegetation encroachment and its influence on sediment erosion and deposition (Table 2). In addition, the monitoring and research associated with these projects supports an enhanced understanding of natural processes that affect archeological and cultural sites, sandbar change, and geomorphic processes. The projects in this theme also directly support **LTEMP Resource Goal 8** (Tribal Resources) by providing information on the physical conditions affecting cultural resources important to Tribes. The projects in this theme also directly support **LTEMP Resource Goal 11** (Riparian Vegetation) by providing ongoing information on the state of riparian vegetation along the mainstem, for understanding the effects of dam operations on riparian vegetation and associated resources, and for understanding how riparian vegetation is interacting with sediment and sandbars to affect physical and recreational resources (Table 2).

Humpback Chub, Rainbow Trout, Warm Water Native and Non-Native Fish, and Aquatic Ecology

This theme includes all work performed under Projects F, G, H, and I. Project F provides important monitoring information on aquatic ecology of the CRe and baseline information that will be used to determine how the aquatic food base responds to LTEMP flow experiments such as macroinvertebrate production flows. Project G provides important monitoring information on humpback chub and other native and nonnative fish populations in the CRe and research activities and compliance obligations associated with the BiOp. Project H monitors trout population throughout the CRe and utilizes a combination of field, modeling, and laboratory techniques to evaluate the response of trout to experimental flows including trout management flows (TMFs), HFEs, equalization flows, and macroinvertebrate production flows (MPFs). Project I provides scientific information that facilitates effective management of warm-water native and non-native fish through system-wide monitoring efforts as well as a combination of field and laboratory research.

The projects in this theme are used to evaluate progress towards **LTEMP Resource Goals 2, 3, 5, 9, and 10** (Natural Processes, Humpback Chub, Other Native Fish, Rainbow Trout Fishery, and Nonnative Invasive Species) by providing information on the general health of the aquatic ecosystem of the CRe, including native and nonnative fish populations, as well as the results of experiment such as MPFs (Table 2). The projects in this theme evaluate progress towards

LTEMP Resource Goals 3 and 5 (Humpback Chub and Other Native Fish) by providing long-term monitoring of native fish populations that allows for the detection of trends and the testing of hypotheses in regard to temporal variation. These projects also support a number of experimental actions regarding native fishes such as spring and fall HFEs, humpback chub translocations, MPFs, extended duration HFEs, and proactive spring HFEs as well as compliance obligations under the BiOp. In addition, these projects also evaluate progress towards **LTEMP Resource Goals 9 and 10** (Rainbow Trout Fishery and Nonnative Invasive Species) by providing long-term monitoring of trout populations and invasive species, to gain a better understanding of the effects of experimental flows on rainbow trout and brown trout recruitment, growth, survival, dispersal, and movement, and to better understand adverse interactions of native fishes with nonnative, invasive warm-water fishes (Table 2).

Socioeconomics and Hydropower

This theme includes all work performed under Projects J and N. Project J is designed to identify cultural and economic values of downstream resources and hydropower and evaluate how these metrics are influenced by dam operations including proposed experiments under LTEMP. Project N will focus on monitoring and research opportunities to provide information related to the hydropower and energy objectives identified in the LTEMP ROD. The projects in this theme will be used to evaluate progress towards **LTEMP Resource Goals 3, 4 and and 10** (Humpback Chub, Hydropower and Energy, and Nonnative Invasive Species) by incorporating economic and hydropower information with physical and biological data and predictive models that improve management of downstream resources and hydropower and facilitate the prioritization of monitoring and research. Additionally, the projects in this theme directly support **LTEMP Resource Goal 8** (Tribal Resources) by identifying tribal member preferences and values associated with management of downstream resources (Table 2).

GCMRC Administration and Support

This theme includes all work performed under Projects K and M. Project K provides geospatial and data technology support to Projects A-J and Appendix 1. Project M provides administrative assistance, logistics support staff, and leadership for GCMRC. The projects in this theme indirectly support all LTEMP Resource Goals, experiments, and compliance obligations. This is accomplished by providing data processing, data management and documentation, geospatial analysis, and access to data holdings. In addition, the projects in this theme also provide funding for travel and training costs for administrative personnel, operating expenses and costs associated with GCMRC staff to travel to AMWG and TWG meetings.

Hypotheses and Science Questions

The hypotheses and science questions to be considered and/or tested during the period of this work plan are provided in section 3 of each project narrative. In many instances, these hypotheses and science questions will be carried forward and included in future work plans. This is due to the geographic and temporal scopes of resources and processes of interest and the condition-dependent nature of the majority of the flow and non-flow experiments prescribed by the LTEMP ROD. For example, proactive spring HFEs are to be tested in years where releases from Glen Canyon Dam are ≥ 10 million acre feet. The general hypothesis to be tested in this case is; will proactive HFEs conserve sediment and lead to more sandbar building than would occur if they were not implemented. It is likely that this experimental action and its associated hypothesis will need examination in future work plans because of the uncertainty associated with when triggering conditions will occur and how frequently and the stipulation in the LTEMP ROD that proactive spring HFEs are prohibited in the first two years of the LTEMP (until water year 2020). In addition, proactive spring HFEs are prohibited in years with a sediment-triggered spring HFE or in water years where an extended-duration fall HFE has occurred. It is also likely that more than one trial will be needed to accept or reject this hypothesis. Other experiments and their associated hypotheses, such as extended duration HFEs and Trout Management Flows, are also likely to be carried forward into future work plans since they are similarly constrained due to dependencies on specific conditions existing or developing as well as having been identified as mutually exclusive with other experiments in the LTEMP ROD.

The condition-dependent nature of most experimental actions identified in the LTEMP limits the value of developing and implementing long-term, set study designs (e.g., block designs) due to uncertainty associated with when and how frequently conditions to trigger experiments will occur. Instead, we believe a more tractable and effective approach is to develop models representing competing hypothesis and update statistical support for competing models (hypotheses) based on monitoring in years with and without relevant experimental flows. In many instances, models were developed for the LTEMP process and these models (or modifications of them) can be a useful starting point for incorporating data studied during this and future work plans. As an example, GCMRC scientists plan to modify the rainbow trout model used in the LTEMP process so that it can be updated annually to provide not only estimates of rainbow trout recruitment and outmigration but also relative support for different hypothesized drivers as well as estimates of the effects of various experimental flows including spring and fall HFEs and trout management flows (see Project H.2). Approaches that simultaneously consider multiple competing hypotheses and the relative support for these different hypotheses can be extremely useful in the study of complex systems. Data can be evaluated against a set of hypotheses as it is generated, as opposed to examining falsifiable hypotheses one at a time over multi-year periods often in the context of multiple varying and uncontrollable outside factors. The latter of these study types are prone to being confounded by stochastic events and are not responsive to the needs of decision makers and managers since complete analyses can only be conducted after years of data collection.

The Final Report of the 2016 Fisheries Program Review (https://www.usbr.gov/uc/rm/amp/twg/mtgs/17apr20/Attach_06a.pdf) noted that the GCDAMP has employed a “resilience-experimentalist” approach to adaptive management (see McFadden and others 2011) which implements long-term experimental studies based on falsifiable hypotheses as described above. The fisheries panel recommend instead, a “decision-theoretic” framework be employed. In this approach, a set of alternative hypotheses about a particular resource or question are developed and then evaluated by using collected data to compare predicted outcomes of the models representing competing hypotheses relative to observed outcomes. The models representing competing hypotheses are then revised based on the updated hypotheses about resource interactions. Several projects in the FY2018-20 TWP employ multiple hypothesis testing and model selection, the best examples being Project E, Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future, Project G, Humpback Chub Population Dynamics throughout the Colorado River Ecosystem, and Project J, Socioeconomic Research in the Colorado River Ecosystem. This approach aligns with the decision-theoretic framework mentioned above and will speed learning about the role nutrients play as drivers of the aquatic ecosystem and the status and trends of humpback chub in the CRe.

Compliance – Endangered Species Act & National Historic Preservation Act

The BiOp for the LTEMP ROD (U.S. Department of the Interior, 2016b) concludes that the actions proposed under the LTEMP ROD “may affect the endangered humpback chub and its critical habitat, the endangered razorback sucker and its critical habitat, and the endangered Kanab ambersnail.” The BiOp also concludes that while incidental take of these species is “reasonably certain to occur”, the level of anticipated take is not likely to result in the jeopardy of any these species. This is due in part to conservation measures to be conducted as part of implementation of the LTEMP ROD. These conservation measures are designed to limit or lower the impact of flow and non-flow actions on these species and their habitat under the LTEMP or to benefit these species. The conservation measures include a number of ongoing activities and also identify new actions to be undertaken. Ongoing actions specific to humpback chub include translocations of young fish into tributaries and associated monitoring, maintenance of a refuge population at a federal fish hatchery, and continuation of nonnative fish control efforts including evaluation of new methods (e.g., chemical piscicides), in tributaries prior to humpback translocations (see Chapter 1 and Project Elements G.1, G.2, and G.7). Other ongoing activities include monitoring the status and trends of various humpback chub population segments in the

Little Colorado River (LCR), aggregations of humpback chub in the mainstem Colorado River, and in areas outside of known concentrations of humpback chub. Other activities include determining the biological and environmental drivers of these population segments and monitoring humpback chub and other fishes for parasites and signs of disease. New actions focus on identifying and evaluating other tributaries, specifically including Havasu Creek, as potential locations for future humpback chub translocations (see Project Elements G.1, G.2, G.3, G.4, G.5, G.6, and G.8).

For razorback sucker, efforts to monitor larval and small-bodied fishes in the mainstem Colorado River would continue (see Chapter 1). A number of actions to benefit all native aquatic species were also identified as conservation measures. These include ongoing efforts to determine the best and most efficient approaches to renovate Bright Angel Creek and Havasu Creek for humpback chub and other native fishes and to complete and evaluate the effectiveness of the 5-year experimental trout removal from Bright Angel Creek and the Bright Angel Creek inflow reach of the Colorado River (see Chapter 1). Also included are new actions such as evaluating temperature control methods, both warming and cooling, and methods to prevent fish passage at Glen Canyon Dam. Other issues to be addressed include those related to warmwater nonnative fishes in the backwater slough at river mile -12 in Glen Canyon, developing a plan for rapid response to control emerging unwanted nonnative species, and considering the experimental use of trout management flows to control brown trout in Glen Canyon (see Chapter 1 and Project Elements H.1 and H.3).

An LTEMP goal specific to archaeological sites and other cultural resources is to "[m]aintain the integrity of potentially affected NRHP-eligible or listed historic properties in place, where possible, with preservation methods employed on a site-specific basis." At the same time, the LTEMP ROD acknowledges that dam operations may have adverse effects on historic properties through "inundation and exposure, changing vegetation cover, streambank erosion, slumping and influencing the availability of sediment", any or all of which may require Reclamation to mitigate those effects through site-specific stabilization treatments, excavations, or other means. The LTEMP ROD commits Reclamation to develop a Historic Preservation Plan (HPP) to guide future monitoring and management of cultural resources affected by dam operations. Consequently, a substantial portion of Reclamation's FY2018-20 work plan and budget is devoted to developing this HPP or various ancillary components of it (see Projects D1 through D11 in Chapter 1). At the same time, there continues to be a lack of stakeholder consensus surrounding the role of dam operations in affecting cultural resource condition and integrity warranting additional scientific research and monitoring to help resolve areas of uncertainty related to the effects of dam operations. Therefore, GCMRC has proposed a limited monitoring and research program specifically designed to address several key concerns regarding cultural resources and their relevance to dam operations. The two elements in GCMRC's Project D are specifically designed to focus on questions about how, in what respects, and at what rates do dam operations and proposed non-flow actions affect the LTEMP goal of maintaining and preserving cultural resources in place. Answering these questions using credible scientific, peer-reviewed methods will help to inform managers and GCDAMP stakeholders about how daily dam operations, experimental flows, and non-flow management actions such as vegetation removal, affect the condition of cultural resources and the landscape context in which they are situated. Additionally, it will help to identify the most cost-effective and reliable options for mitigating dam-related effects over the 20-year course of the LTEMP and preserving these non-renewable resources into the future.

Work Plan Process

As noted in the LTEMP Science Plan (VanderKooi and others, 2017), successful implementation of the LTEMP ROD will require close cooperation and coordination among managers, stakeholders, and scientists. The GCDAMP Triennial Budget and Work Plan Process approved by the TWG in October 2016 (https://www.usbr.gov/uc/rm/amp/twg/mtgs/16oct18/Attach_09b.pdf) identifies the process for work plan development and revision. However, portions of the work plan may also need to be revised based on scientific learning, changing environmental conditions, management decisions, policy changes, budget considerations, or other unexpected developments. The condition-dependent nature of flow and non-flow experiments, both to trigger actions and curtail them, will require not only data collection, modeling, and analysis but also frequent communication regarding results and the application of those results to decision making. Flexibility and a willingness to be responsive to change will be needed. The Annual Reporting Meeting each January is critical for providing information on the status of key resources, progress of activities identified in specific project elements, identifying experiments or actions that may occur each year, and discussing possible revisions to the work plan. In addition, updates of ongoing work and results from research and monitoring will continue at quarterly TWG meetings and more frequently as needed. As we have done during the development of the FY2018-20 TWP, GCMRC looks forward to working closely with the TWG and AMWG throughout the life cycle of this and future work plans.

References

Glen Canyon Dam Adaptive Management Program, 2001, Strategic plan—Glen Canyon Dam Adaptive Management Program—final draft: Salt Lake City, Utah, Adaptive Management Work Group, 52 p. plus appendices, http://www.usbr.gov/uc/rm/amp/pdfs/sp_final.pdf.

McFadden, J.E., Hiller, T.L., and Tyre, A.J., 2011, Evaluating the efficacy of adaptive management approaches—Is there a formula for success?: Journal of Environmental Management, v. 92, no. 5, p. 1354-1359, https://doi.org/10.1016/j.jenvman.2010.10.038.

Schmidt, J.C., Webb, R.H., Valdez, R.A., Marzolf, G.R., and Stevens, L.E., 1998, Science and values in river restoration in the Grand Canyon: BioScience, v. 48, no. 9, p. 735-747, http://www.jstor.org/stable/1313336.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Department of the Interior, 2007, Record of decision—Colorado River interim guidelines for lower basin shortages and the coordinated operations for Lake Powell and Lake Mead: Washington, D.C., Office of the Secretary of the Interior, 59 p., http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam, Colorado River storage project, Arizona—Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, 337 p. plus appendices, http://www.usbr.gov/uc/envdocs/eis/gc/gcdOpsFEIS.html.

U.S. Department of the Interior, 2011a, Environmental assessment—Development and implementation of a protocol for high-flow experimental releases from Glen Canyon Dam, Arizona, 2011 through 2020: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 176 p. plus appendices, http://www.usbr.gov/uc/envdocs/ea/gc/HFEProtocol/HFE-EA.pdf.

Bureau of Reclamation, 2011b, Environmental Assessment—Non-native fish control downstream from Glen Canyon Dam: Salt Lake City, Utah, Department of the Interior, Bureau of Reclamation, 112 p. plus appendices, https://www.usbr.gov/uc/envdocs/ea/gc/nnfc/NNFC-EA.pdf.

U.S. Geological Survey, 2007, Strategic science plan to support the Glen Canyon Dam adaptive management program, Fiscal years 2007-2011: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, in cooperation with the Glen Canyon Dam Adaptive Management Program (GCDAMP), 149 p., http://gcdamp.com/images_gcdamp_com/f/fc/Strategic_Science_Plan_FY07-11_%281%29.pdf.

U.S. Geological Survey, 2011, General core monitoring plan for the Glen Canyon Dam Adaptive Management Program—final draft: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 134 p., https://www.usbr.gov/uc/rm/amp/twg/mtgs/11oct20/Attach_08a.pdf.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Sankey, J.B., Yackulic, C.B., and Schmidt, J.C., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

Project A: Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem

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2. Project Summary

The primary linkage between Glen Canyon Dam (GCD) operations and the characteristics of the physical, biological, and cultural resources of the CRe downstream from GCD is through the stage, discharge, water quality, and sediment transport of the Colorado River. This project makes and interprets the basic measurements of these parameters at locations throughout the CRe. The data collected by this project are used to implement the HFE Protocol (i.e., trigger and design HFE hydrographs), to evaluate the reach-scale sand mass-balance response to the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), and to evaluate the downstream effects of releases conducted under the LTEMP EIS (U.S. Department of the Interior, 2016a, b). The data collected by this project are also required by the other physical, ecological, and socio-cultural projects funded by the GCDAMP. Most of the project funds support basic data collection at USGS gaging stations, with only a small amount of project funds supporting interpretation of basic data. The funds requested under this proposal cover only ~70% of the costs required to operate and interpret data at the network of USGS gaging stations used by this project; other funding for this network is provided to the USGS Arizona Water Science Center from funds appropriated by Congress for the USGS, the Bureau of Land Management, and the Arizona Department of Environmental Quality (AZDEQ). This project is designed to provide measurements of stage (i.e., water elevation), discharge (i.e., streamflow), water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minute) to resolve changes in these parameters and to allow accurate determination of suspended-sediment loads for use in sediment budgeting. The proposed monitoring under this project will be very similar to that conducted over the last 5-10 years.

The 3 elements of this project are as follows:

1) Stream gaging:

This element partially funds the collection, serving, and interpretation of continuous 15-minute measurements of stage and discharge on the main-stem Colorado River at USGS streamflow gaging stations located at river miles[1] (RM) 0, 30, 61, 87, 166, and 225, and at gaging stations on the major tributaries and in a representative subset of the smaller, formerly ungaged tributaries (Water Holes Canyon, Badger Creek, Tanner Wash, House Rock Wash, North Canyon, Shinumo Wash, and Bright Angel Creek).

2) Water quality:

This element funds the collection, serving, and interpretation of continuous 15-minute measurements of water temperature, specific conductance (a measure of salinity), turbidity, and dissolved oxygen at the above-mentioned six mainstem Colorado River gaging stations, as well as continuous measurements of water temperature at additional stations on the Colorado River and in the major tributaries. In addition, this element provides a small amount of funding toward the logistics required to collect samples for laboratory water-chemistry analyses (including nutrients) at gaging stations on the Colorado River.

3) Sediment transport and budgeting:

This element funds the collection, serving, and interpretation of continuous 15-minute measurements and also episodic measurements of suspended sediment and bed sediment at the above-mentioned gaging stations on the Colorado River and its tributaries. The continuous suspended-sediment measurements at the six mainstem Colorado River gaging stations, and the episodic suspended-sediment measurements in the tributaries are used in the construction of mass-balance sand budgets. These budgets inform scientists and managers on the effects of dam operations on the sand mass balance in the CRe between Lees Ferry and Lake Mead divided into 6 reaches (Figure 1). Increases in the sand mass balance in a reach indicate an increase in the amount of sand in that reach and therefore an increase in the amount of sand available for sandbar deposition during HFEs, whereas decreases in the sand mass balance in a reach indicate a net loss of sand from that reach. All measurements made by this project are made using standard USGS and other peer-reviewed techniques. All of these measurements can be plotted and/or downloaded at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. Plots of continuous parameters can be made in time-series or duration-curve formats. In addition, the user-interactive mass-balance sand budgets for the six CRe reaches are available at this website (Sibley and others, 2015). In addition to the collection and serving of the basic streamflow, water-quality, and sediment-transport data, time is spent in this project interpreting the data and reporting on the results and

[1] The use of river miles has a historical precedent and provides a reproducible method for describing locations along the Colorado River below Glen Canyon Dam. Lees Ferry is the starting point, river mile 0, with mileage measured upstream, with negative values (–) and downstream, with positive values (+).

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. To date, this ongoing project has published over 80 peer-reviewed journal articles, books, proceedings articles, and USGS reports, a full listing of which are available at: https://www.usgs.gov/centers/sbsc/science/fluvial-river-sediment-dynamics?qt-science_center_objects=1 - qt-science_center_objects. This website also provides urls to download these publications.

3. Hypotheses and Science Questions

The hypotheses and science questions to be considered and/or tested during the period of this work plan for this project are:

- Is there a "flow-only" operation (that is, a strategy for dam releases, including managing tributary inputs with HFEs, without sediment augmentation) that will restore and maintain sandbar habitats over decadal timescales?
- How do dam release temperatures, flows (average and fluctuating component), meteorology, canyon orientation and geometry, and reach morphology interact to determine mainstem and nearshore water temperatures throughout the CRe?

4. Background

Systematic measurements of streamflow and water quality, 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 water temperature, and episodic measurements of other water-quality parameters, were made by the USGS at multiple gaging stations in the CRe and on key tributaries. This intensive period of measurements ended in the early 1970s (Andrews, 1991; Topping and others, 2000a). Concern about the effects of the operation of GCD 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 described herein.

The operation of GCD controls the CRe because it is the dominant controller of river stage, discharge, and water quality, and is a primary regulator of sediment transport, erosion, and deposition (Topping and others, 2000, 2003; Rubin and Topping, 2001, 2008; Gloss and others, 2005). Water temperature, salinity, dissolved oxygen, and water chemistry at the foot of the dam are determined by the physical and chemical characteristics of the reservoir water at the penstock and/or jet-tube elevations on the upstream face of the dam (Vernieu and others, 2005). Because the amount of water supplied by downstream tributaries is small and large floods on these tributaries are infrequent, dam operations largely determine stage, discharge, and key water-quality parameters (water temperature and salinity) throughout the CRe (Wiele and Smith, 1996; Wiele and Griffin, 1998; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010). In addition, because sediment transport in the CRe is controlled by both changes in discharge and changes in bed-sediment grain size (Rubin and Topping, 2001, 2008), and because dam operations control discharge, the operation of GCD acts as a primary regulator of sediment transport in the CRe. As dam operations regulate the amount of sediment in the water column (i.e., suspended sediment), and because suspended sediment largely determines turbidity (Voichick and Topping, 2014), dam operations therefore influence downstream turbidity in the CRe. Finally, because dam operations largely determine water temperature and also influence turbidity, other downstream water-quality parameters regulated by water temperature and turbidity are also affected by dam operations, e.g., dissolved oxygen at locations far downstream from the dam (Hall and others, 2015) (dissolved oxygen is generally negatively related to water temperature, turbidity, and suspended-sediment concentration, e.g., data at: https://www.gcmrc.gov/discharge_qw_sediment/).

Suspended sediment is an important water quality parameter in the CRe for several reasons. First, deposition and/or erosion of the eddy sandbars and channel-margin deposits important to many biological, cultural, and recreational resources are directly controlled by the transport of sand (Gloss and others, 2005). Because the amount of sand transported as bedload is much smaller (typically <5%) than the amount of sand transported in suspension at moderate and higher dam releases (Rubin and others, 2001), the rate of deposition and/or erosion of eddy sandbars and channel-margin deposits is related by mass conservation to spatial gradients in the suspended-sand flux (after Exner, 1920, 1925). By theory (Grams and others, 2013) and experiments (Schmidt and others, 1993), eddy-sandbar deposition is most efficient when the flux of suspended sand is the highest in the main channel of the river. Because suspended-sand flux is the depth-integrated product of suspended-sand concentration and water discharge, maximum main-channel sand flux occurs when the concentration of suspended sand is the highest (determined by the water discharge, bed-sand grain-size distribution, and areal amount of sand on the bed, e.g., Topping and others, 2007) and the velocity is the highest (i.e., at higher discharge). Under this condition, the convergence (i.e., negative spatial gradient) in the sand flux between the main channel and the riverbank in an eddy is the largest, leading to the greatest sand deposition rates in an eddy (Topping and others, 2010; Grams and others, 2013). Therefore, by the physics that control eddy-sandbar deposition, eddy sandbars are built most effectively when the discharge is high and the amount of finer sand in a reach is maximized (Schmidt and Grams, 2011). Thus, effective management of eddy sandbars (and associated resources) in different reaches of the Colorado River requires managers to know when the amount of finer sand in those specific reaches is enriched so that artificial controlled floods (now known as HFEs) can be released from the dam (Wright and others, 2005, 2008; Topping and others, 2010).

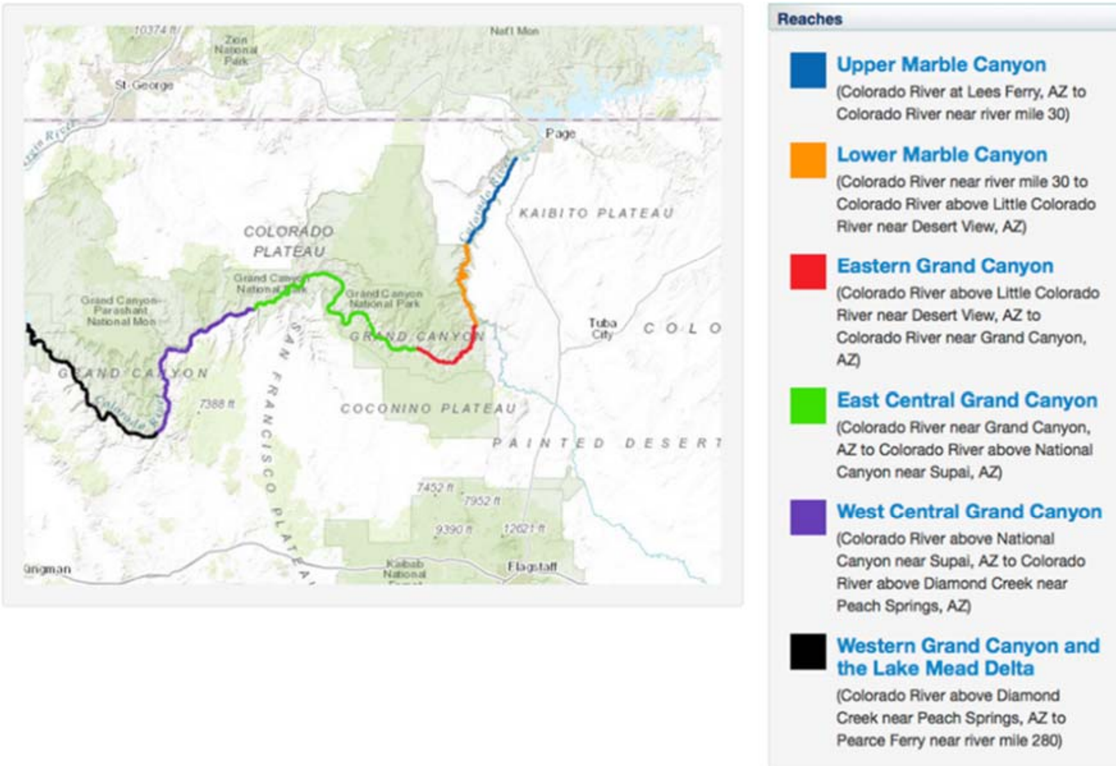

Figure 1. Map showing the extents of the six reaches of the Colorado River in Glen and Grand Canyons in which mass-balance sand budgets are constructed. Map taken from this project's website (https://www.gcmrc.gov/discharge_qw_sediment/, U.S. Geological Survey, 2017).

The second major reason as to why suspended sediment is an important water quality parameter is that it largely determines turbidity, and therefore influences the aquatic and fish ecology of the river (Voichick and others, 2016). The endemic fishes of the CRe evolved in a highly turbid river (Gloss and Coggins, 2005). Turbidity is primarily determined by the concentration of suspended silt and clay and, to a lesser degree, suspended sand (Voichick and Topping, 2014). Because closure of GCD cut off the upstream supply of silt and clay, the post-dam Colorado River in Marble and Grand Canyons is much less turbid than ever occurred naturally (Voichick and Topping, 2014). Although on average turbidity increases in a stepwise fashion in the downstream direction (at the mouths of the Paria and LCR), the Colorado River in the CRe is now moderately to highly turbid only during periods of tributary flooding (Voichick and Topping, 2014).

The transport of suspended sediment in the CRe is controlled by both the discharge released from the dam and the episodic tributary resupply of sand, silt, and clay (Topping and others, 2000b). By cutting off the majority of the sediment formerly supplied to the Colorado River in Marble and Grand Canyons, closure of GCD in 1963 reduced the upstream supply of sand, silt and clay at the upstream boundary of Grand Canyon National Park to ~5% of its pre-dam amount, and reduced the upstream supply of sand at this location to ~6% of its pre-dam amount

(Topping and others, 2000a). Although other tributaries downstream from the dam do episodically supply sediment and sometimes in large amounts (Griffiths and others, 2015, in press), the majority of silt and clay supplied to the CRe is now supplied by the LCR and the majority of the sand supplied to the CRe is now supplied by the Paria River (U.S. Geological Survey, 2017). Although the LCR was historically an important supplier of sand, recent analyses of suspended-sediment data from the LCR indicate that the amount of sand supplied from this river has decreased substantially over time and may still be decreasing into the future (all 1949-2016 sand-transport data available at https://www.gcmrc.gov/discharge_qw_sediment/). At most flows, silt- and clay-sized sediment has negligible interaction with the bed sediment by Rouse mechanics (e.g., McLean, 1992). Consequently, silt and clay is transported as washload and is quickly transported downstream in the Colorado River following resupply during tributary floods. In contrast, because of the strong interaction between the suspended sand and the bed sediment, the changes in bed-sand grain size associated with the tributary resupply of sand exert a strong and longer-lasting control on the downstream transport of sand (Rubin and Topping, 2001, 2008; Topping and others, 2010). The fining of the bed sand in the Colorado River immediately following a tributary flood and the daily increases in discharge caused by dam operations can both cause similar magnitudes of increase in suspended-sand concentration of 100% to over 1,000% (U.S. Geological Survey, 2017).

The finding that sand transport in the post-dam Colorado River was essentially co-equally regulated by changes in discharge and changes in bed-sand grain size refuted key aspects of the 1995 GCD EIS (U.S. Department of the Interior, 1995). This 1995 document assumed that suspended-sand transport was regulated only by changes in discharge (Rubin and others, 2002). At moderate and higher dam releases, the residence time of tributary-supplied sand in the CRe is much shorter than assumed in the 1995 EIS (Topping and others, 2000b; Rubin and others, 2002; Wright and others, 2005). Thus, the 1995 EIS management strategy – of using multi-year accumulation of tributary-supplied sand for sandbar rebuilding in the CRe during relatively rare HFEs – was not valid (Rubin and others, 2002; Wright and others, 2005). Because both discharge and bed-sand grain size exert strong controls on sand transport, and because a multi-year residence time of tributary-supplied sand cannot be assumed, continuous suspended-sediment measurements were thus required to evaluate the effects of dam operations on sediment transport in the CRe, and thus required by managers to know when sufficient sand was available to conduct an HFE (Wright and others, 2005; Wright and Kennedy, 2011; Grams and others, 2015).

Through any given river cross section, the transport of sediment is regulated by the physical interaction of the flow with the local channel geometry and by the grain-size distribution of the bed sediment (Rubin and Topping, 2001, 2008; Topping and others, 2007). Thus, at a constant discharge (i.e., dam release), the downstream transport of sediment will vary as a function of longitudinal differences in channel geometry and bed-sediment grain size (Topping and others, 2000b). Channel geometry is not constant in the longitudinal direction along the Colorado River and bed-sediment grain size varies longitudinally because, after resupply by tributaries, sediment travels downstream in the Colorado River as elongating sediment waves (Topping and others, 2000b). These conditions lead to longitudinally nonuniform sediment transport in the CRe, even under conditions of constant discharge, e.g., during HFEs or equalization releases. Sediment transport does not necessarily monotonically increase in the downstream direction under constant discharge, even when the discharge is high (Topping and others, 2010). For example, during the 2011 equalization releases, sand transport at the Colorado River above Diamond Creek gaging station was less than that at upstream gaging stations, leading to net deposition of sand in the west-central Grand Canyon reach of the Colorado River (between RM 166 and 225) even though sand was eroded from all upstream reaches during these high-discharge releases (U.S. Geological Survey, 2017). Because of the always present, but temporally varying, longitudinal nonuniformity in sediment transport in the Colorado River, continuous sediment-transport measurements are required at locations bracketing key reaches of interest in order to document how dam operations affect sediment resources in the CRe (Wright and others, 2005).

The longitudinal nonuniformity in sediment transport, and specifically in sand transport, leads to the condition in the CRe where, during discrete time periods, sand gets deposited in long reaches while it gets eroded from other long reaches. Thus, it is incorrect to ever assume that the CRe as a whole, or even Marble or Grand Canyons as a whole, undergo similar changes in the mass of sand stored in these long river segments. Furthermore, it is incorrect to assume that changes in sand mass get more positive progressively farther downstream in the CRe. For example, during the post-2012 period of the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), the two long reaches of the CRe that have generally experienced erosion of sand are not at the upstream end of the CRe, but rather are the eastern Grand Canyon reach (RM 61-88) immediately downstream from the LCR and the west-central Grand Canyon reach (RM 166-225) (Figure 2, U.S. Geological Survey, 2017).

In addition, although HFEs invariably erode large amounts of sand from the CRe in the process of building higher-elevation sandbars (Rubin and others, 2002; Wright and others, 2005), this erosion is not uniformly distributed in the CRe, with long segments of the CRe actually gaining sand during HFEs. Even though net erosion of sand occurred in other reaches during the 2012, 2013, and 2014 HFEs, net deposition of sand occurred during these HFEs in the lower Marble Canyon reach (RM 30-61) and the east-central Grand Canyon reach (RM 88-166) (U.S. Geological Survey, 2017). The spatial patterns of erosion and deposition of sand were somewhat different during the 2008 and 2016 HFEs. In the 2008 HFE, net erosion of sand occurred in all reaches except the east- and west-central Grand Canyon reaches (RM 88-166 and 166-225), both of which experienced net sand deposition (U.S. Geological Survey, 2017). In the 2016 HFE, net erosion of sand occurred in all reaches except the east-central Grand Canyon reach (U.S. Geological Survey, 2017).

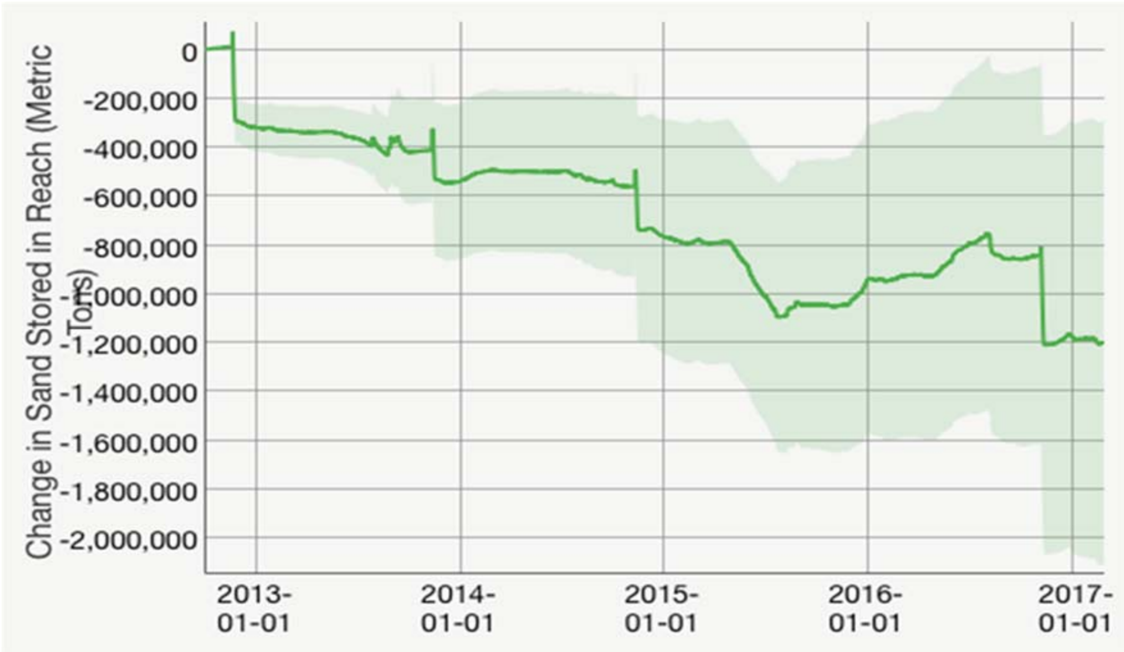

Figure 2. Measured change in sand mass in the west-central Grand Canyon reach of the Colorado River in the CRe (RM 166-225) during 10-1-2012 through 3-1-2017. Given the uncertainty (light green region) in this continuous mass-balance sand budget, this reach has lost between 290,000 and 2,100,000 metric tons of sand during this period. Plot from this project's website at https://www.gcmrc.gov/discharge_qw_sediment/ (U.S. Geological Survey, 2017).

Monitoring of changes in the sand resources in the CRe therefore requires a strategy where the CRe is divided into key reaches on the partial basis of the locations of major tributaries that affect the sediment supply and potentially the water quality of the CRe. This is the strategy that has been used in this project since it began in the early 2000s. Therefore, in this ongoing project, the CRe was divided into seven monitoring reaches bracketed by USGS gaging stations (described later in this proposal). At each of these six gaging stations, stage, discharge, water temperature, specific conductance, dissolved oxygen, and turbidity are measured continuously at 15-minute intervals. At the downstream five of these stations in Marble and Grand Canyons, suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand grain size are also measured at 15-minute intervals. These sediment-transport data are used to compute the sand loads that are, in turn, used in the six user-interactive mass-balance sand budgets served on this project's website (Sibley and others, 2015). These sand budgets are used to evaluate the near-realtime continuous effects of dam operations (including special LTEMP releases for trout management and invertebrates) on sand resources throughout the CRe, and used in the design and evaluation of HFEs.

Research on the Colorado and on other rivers has shown that, to be meaningful, measurements of stage, discharge, water temperature, specific conductance, turbidity, dissolved oxygen, and suspended sediment must be made at temporal intervals shorter than those over which these parameters vary. Owing to the effects of dam operations and tributary floods, substantial changes in all of these parameters occur at times over timescales less than one hour (Figure 3, Wiele and Smith, 1996; Wiele and Griffin, 1998; Topping and others, 2000b, 2003, 2010; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010, 2014; U.S. Geological Survey, 2017). This ongoing project was therefore designed to provide measurements of stage, discharge, water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minutes) to capture the variability in these parameters, and in the case of suspended sediment, calculate accurate sediment loads. Collection of such data at 15-minute intervals is the USGS standard. Months to years of data collected at this resolution easily fit on modern dataloggers, result in no additional processing time in the office, and result in no additional financial cost to the project.

5. Proposed Work

The work proposed herein is for the continuation of an ongoing project (approved by the GCDAMP TWG as core monitoring in 2007) to collect, serve, and interpret stage, discharge, water-quality (temperature, specific conductance, turbidity, dissolved oxygen), and sediment-transport data at stations located on the Colorado River in the CRe and on key tributaries. In addition, we propose to continue the web-based construction, serving, and analysis of the continuous mass-balance sand budgets used to evaluate the effects of dam operations on sand storage in the CRe. A map showing the locations at which data are collected/utilized by this project is at: https://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP; note that the GCDAMP does not fund the data collection at all of the stations on this map. Selection of the locations of the stations at which data are collected by this project was largely based on the need to resolve longitudinal differences in sediment storage in key river segments that bracket major tributaries. Elsewhere, data-collection station locations were established to support other GCDAMP-funded projects or to reoccupy former USGS gaging stations.

The data collected by this project will be used to evaluate the near-realtime effects of all LTEMP dam releases on water elevation (stage), discharge, water quality, sediment transport, and sediment storage in the CRe (U.S. Department of the Interior, 2016a, b). The continuous mass-balance sand budgets provide the measurement-based "ground-truthing" of the Sand Mass Balance Index (SMBI) developed in Appendix E of the LTEMP EIS (U.S. Department of the Interior, 2016a). Higher values of the SMBI in the LTEMP EIS were taken as indicators of increased sand storage in the CRe, with increases in sand storage indicating an increase in the sand available to be deposited in sandbars during HFEs. In addition, the sediment-transport data and mass-balance sand budgets are used under the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015) to work collaboratively with the Bureau of Reclamation to trigger HFEs, design the hydrograph of HFEs, and evaluate the effects of HFEs on sand storage in the CRe.

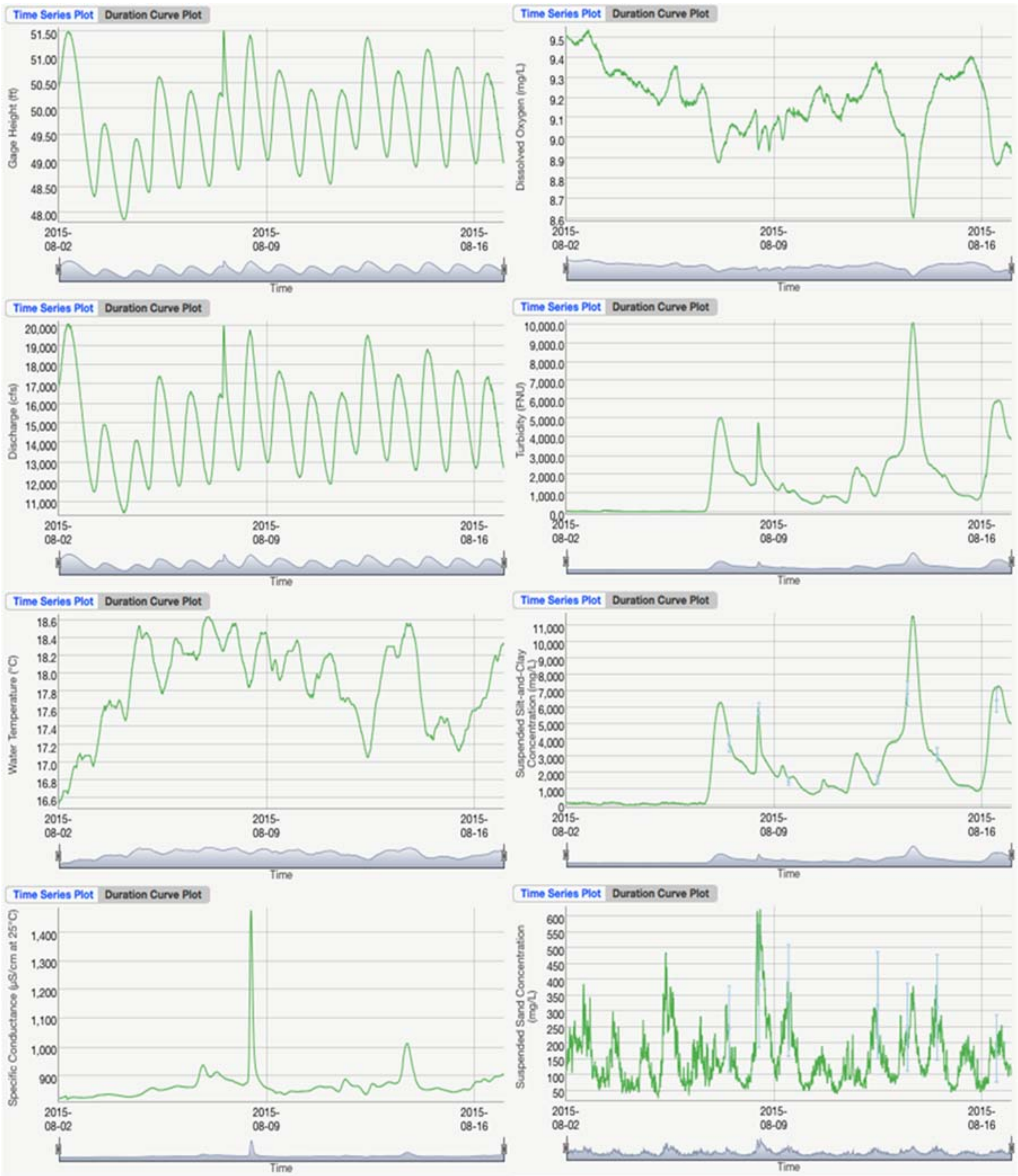

Figure 3. Plots of 15-minute gage height (i.e., stage, water elevation), water discharge, water temperature, specific conductance, turbidity, dissolved oxygen, suspended-silt-and-clay concentration, and suspended-sand concentration for the two-week period 8-2-2015 through 8-16-2015 at the Colorado River above Diamond Creek gaging station. Light blue dots with 95%-confidence-level error bars indicate episodically measured silt and clay concentrations and sand concentrations (from physical suspended-sediment samples) used to verify the two-frequency acoustical suspended-sediment measurements. Variability in each of these parameters over this two-week period arises from the interaction of dam operations with tributary floods. Plots from this project's website are available at: https://www.gcmrc.gov/discharge_qw_sediment/ (U.S. Geological Survey, 2017).

All data collected by this project are served and can be downloaded at this project's website at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. At this website, the user can construct plots in time-series or duration-curve format. In addition, the user can construct interactive plots of the mass-balance sand budgets for the six CRe reaches for any time period for which data exist. The development of this website and its associated database by the collaboration between this project and the USGS Office of Water Information (OWI) (formerly the Center for Integrated Data Analytics) was the most significant product from this project funded under the FY2013-14 GCDAMP work plan. A brief description of the design of the database and website is provided by Sibley and others (2015). The USGS OWI is the leader within the USGS in database and website design. Collaboration with the OWI resulted in a major leap forward in serving data in a user friendly and interactive way, something that had proven problematic for GCMRC to do on its own in previous funding cycles. The tools developed in collaboration with the OWI allow anyone to plot data and construct mass-balance sand budgets for any time period in any reach of the CRe on demand.

A small part of the funding requested under each project element is for the continued maintenance and minor improvement of the database and website by the OWI in Middleton, WI. A minor part of this goes to the housing and secure backup of the servers on which the database and website are located; these servers are physically located at the USGS Earth Resources Observation and Science (EROS) Center near Sioux Falls, SD. In addition to simply maintaining the website during FY2018-20, we plan to optimize plotting speed, add links to publications, and add metadata.

The measurements made by this project are used by all other projects funded by the GCDAMP and are therefore integral to the success of all other projects funded by the GCDAMP. In particular, this project maintains close collaborative ties to Project B (Grams and others, Sandbar and Sediment Storage Monitoring and Research). The external collaborations funded through this project are with three USGS cooperators: the Arizona Water Science Center, the Utah Water Science Center, and the OWI. In addition, academic collaborations (not funded through this project) exist between this project and researchers at Arizona State University, Utah State University, Northern Arizona University, and the University of California–Santa Cruz.

The work proposed herein is segregated into three project elements as described below.

5.1. Project Elements

Project Element A.1. Stream gaging

This element partially funds the continued collection, serving, and interpretation of continuous 15-minute stage and discharge data at gaging stations on the Colorado River and on key tributaries. All measurements of stage and discharge, and all calculations of discharge are made using standard USGS methods. This element provides partial to full funding for these measurements at five gaging stations on the Colorado River at RM 30, 61, 87, 166, and 225 (Griffiths and others, 2012). In addition, this element provides partial to full funding for these measurements at: two gaging stations on the Paria River; four gaging stations on the LCR and in its important sediment-supplying tributary Moenkopi Wash; one gaging station each on Kanab and Havasu Creeks; and at eight stations in a representative sub-sample of the previously ungaged lesser tributaries to Glen, Marble, and Grand Canyons (Griffiths and others, 2014, 2015, *in press*). Of the gaging stations at which stage and discharge measurements are utilized by this project, the only two stations that receive no GCDAMP funds are: Colorado River at Lees Ferry, AZ, and Moenkopi Wash at Moenkopi, AZ. The costs of operating a gaging station for stage and discharge varies substantially between stations. Of the stations funded by this element, the most expensive is the Colorado River above Diamond Creek near Peach Springs, AZ, gaging station at RM 225. This station requires ~$22,000 (including overhead) per year to operate. In contrast, each of the stations on the lesser tributaries and half of the stations in the LCR Basin require only ~$1,200 (including overhead) per year to operate. Even though the Colorado River above Diamond Creek is the most expensive gaging station operated by this project, it is an extremely important station to maintain. In addition to providing key information on the status of the western part of the CRe, it is the gaging station used to measure the ongoing amount of Colorado River sediment filling Lake Mead (a byproduct of the work funded under Project Element 3).

In addition to the collection and serving of stage and discharge data at gaging stations, work proposed under this element will also focus on interpreting these data. During the FY2018-20 period, this project element will fund publications on four topics (partial funding for three of these publications provided under Project Element A.3). First, a major publication will be completed that describes the 1920s-present hydrology of the Paria River and the implications of hydrologic variability/change on the Paria River for sand management in the CRe. The Paria River is the single largest and geographically most important supplier of sand to the Colorado River in the CRe, and current management of sediment in the CRe using HFEs depends on the sand supply from the Paria River (U.S. Department of the Interior, 2011, 2016 a, b). Thus, because changes in the hydrology of the Paria River directly result in changes in the sand supply of the Paria River, this publication will be of great importance to river managers. Second, a publication will be completed that uses stream-gaging data funded by this element in the LCR and Moenkopi Wash to evaluate the decrease in sand transport in the LCR. Third, a publication will be completed that uses the stream-gaging data funded by this element to evaluate how the flood history of the LCR has affected the native fish habitat in the lowermost part of this river.

Finally and fourth, a publication will be completed using the stream-gaging data funded by this element in the mainstem Colorado River to evaluate the effects of all LTEMP flows on sediment transport and storage in the Colorado River.

Project Element A.2. Water quality

This element fully funds the continued collection, serving, and interpretation of continuous 15-minute measurements of water temperature, specific conductance, turbidity, and dissolved oxygen. This element also funds episodic measurements of specific conductance associated with suspended-sediment samples collected in tributaries (these measurements are intrinsic to the laboratory methods for processing the suspended-sediment samples and therefore cost nothing). In addition, this element provides a small amount of the logistical support required to make non-GCDAMP-funded water-chemistry measurements in the Colorado River (including some of the measurements of nutrients used by proposed Project E). All water-quality measurements are made using standard USGS methods. Under this element 15-minute measurements of water temperature, specific conductance, turbidity, and dissolved oxygen are made using YSI multi-parameter sondes in the Colorado River at the gaging stations located at RM 30, 61, 87, 166, and 225. See Voichick and Wright (2007), Voichick (2008), and Voichick and Topping (2010, 2014) for detailed descriptions of these sondes and measurements. In addition, 15-minute measurements of water temperature are made at three additional stations on the Colorado River and at stations near the mouths of the Paria and LCR, and Kanab and Havasu Creeks.

Project Element A.3. Sediment transport and budgeting

This element fully funds the continued collection, serving, and interpretation of continuous 15-minute measurements and also episodic measurements of suspended and bed sediment. All measurements funded under this element are made using standard USGS and other peer-reviewed methods. Under this element, continuous two-frequency acoustical suspended-sediment measurements (calibrated and verified using conventional physical suspended-sediment measurements) are made in the Colorado River at the gaging stations located at RM 30, 61, 87, 166, and 225 using the method of Topping and Wright (2016). In addition to informing river management in the GCDAMP, this acoustical method is now being used to also inform river managers of sediment transport at locations in the upper Colorado River Basin and in the Rio Grande Basin (Dean and others, 2016; Topping and others, 2016). Errors in the conventional suspended-sediment measurements are calculated using the methods of Topping and others (2011) and Sabol and Topping (2013); errors in the acoustical measurements are documented in Topping and Wright (2016). In addition to these measurements on the mainstem Colorado River, episodic suspended-sediment measurements are made at the tributary gaging stations funded under Project Element 1. These measurements are used in conjunction with models (after Topping, 1997) to determine the near-realtime sediment inputs from the Paria and LCR. On the other tributaries, these measurements are used to document the sand, silt, and clay supply from the other major and lesser tributaries and to refine the long-term estimates of the importance of these other tributaries for supplying sediment to the Colorado River. Most of the sediment work on tributaries utilizes automatic samplers and has a large payoff in information for relatively low cost.

In addition to the collection of the sediment-transport data, this element fully funds the web-based construction and analysis of continuous mass-balance sand budgets for the CRe using the continuous suspended-sediment measurements on the Colorado River and the episodic suspended-sediment measurements on the tributaries. These sand budgets have been proven to be an accurate indicator of the change in the amount of sand stored in the Colorado River. In two independent comparisons with sand budgets developed using the channel-mapping data of Project B (Grams and others), these continuous mass-balance sand budgets have agreed with the topographic-based sand budgets of Project B within the uncertainty associated with both methods. These comparisons were conducted between 2009 and 2012 in the lower Marble Canyon reach (RM 30-61) and between 2011 and 2014 in the eastern Grand Canyon reach (RM 61-87). Therefore, the continuous mass-balance sand budgets allow managers to accurately track changes in the amount of sand (with uncertainty) in different reaches of the CRe on an ongoing, near-realtime basis (daily to monthly as needed), and therefore allow managers to continuously evaluate the effects of any flow released from the dam (LTEMP or otherwise) on the sand resources in the CRe on monthly or shorter timescales. Furthermore, these sand budgets provide the "ground truth" for the Sand Mass-balance Index used to evaluate different flow alternatives in the LTEMP EIS (U.S. Department of the Interior, 2016a, b).

In addition to having great utility in evaluating the effects of LTEMP dam releases on the CRe, these mass-balance sand budgets are used in collaboration with the Bureau of Reclamation to trigger, plan, and evaluate HFEs (U.S. Department of the Interior, 2011; Grams and others, 2015). HFEs are triggered and designed on the basis of the Paria-supplied sand that accumulates in Marble Canyon during fall and spring implementation windows (U.S. Department of the Interior, 2011). This process involves using many suspended-sediment samples collected in the Paria River (quickly processed through the GCMRC sediment laboratory) in combination with discharge data (funded under Element 1) and initial model estimates (after Topping, 1997) to determine the near-realtime continuous sand supply from the Paria River. The Bureau of Reclamation then uses this information, along with information on planned dam releases, as input to the sand-routing model of Wright and others (2010). As more suspended-sediment measurements get processed through the laboratory (work funded by this element), the uncertainty is reduced in the calculated Paria River sand supply, and additional model runs are made by the Bureau of Reclamation. As time progresses, the Bureau of Reclamation's model-predictions of sand retention in Marble Canyon are compared against the actual measured sand retention in the continuous mass-balance sand budgets funded under this project element. Because the predictions of the sand-routing model of Wright and others (2010) may be biased, this comparison allows reality-based redesign of each planned HFE hydrograph. Finally, after the completion of each HFE, these sand budgets allow quick post-facto evaluation of the longitudinal effects of each HFE on the sand resources in the CRe.

In addition to the collection and serving of the sediment-transport data and construction of the continuous mass-balance sand budgets, work proposed under this element will also focus on interpreting these data. During the FY2018-20 period, this project element will partially fund publications on three topics (the remaining funding for these three publications provided under Project Element A.1). First, a major publication will be completed that links the hydrology and geomorphology of the Paria River to the amount of sand supplied by the Paria River to the Colorado River. Second, a publication will be completed that documents the causes of the long-term decreases in and likely future magnitude of the amount of sand supplied by the LCR to the Colorado River. In addition, this paper will directly address how changes in sediment transport in the LCR have affected the habitat for native fish in the lower LCR, and how future changes in sediment transport may continue to alter this habitat. Third, a publication will be completed that uses all data collected by this project to evaluate how LTEMP dam releases have affected sand resources during 2018-20.

5.2. Deliverables

Deliverables from this project fall into two categories: serving of data and publication of interpretive products. Perhaps the most important deliverable from this project during FY2018-20 will be the continued serving of all data collected and/or utilized by this project, including the continuous mass-balance sand budgets, at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. In addition, multiple interpretive journal articles and top-tier USGS reports will be published, including on the following topics:

- Analysis of Paria River hydrology 1920s-present with implications for long-term sediment management in the CRe (*lead author Topping*).
- Geomorphology, hydraulic geometry, and sediment transport in the Paria River (*lead author Topping*).
- Sediment transport and geomorphic change in the LCR, with implications for aquatic and riparian habitat in the lower LCR (*lead author Dean*).
- Initial evaluation of LTEMP flows on sediment storage in the CRe (l*ead author Griffiths*).

In addition to these major publications, additional data reports and interpretive reports will be published by project personnel and USGS cooperators. Among these additional reports from USGS cooperators will be a USGS report describing the flood history of the lowermost LCR, and the implications of this flood history for maintenance of native fish habitat.

6. References

Andrews, E.D., 1991, Sediment transport in the Colorado River Basin, *in* Committee to Review the Glen Canyon Environmental Studies Water Science and Technology Board, ed., Colorado River ecology and dam management, Washington, D.C., Proceedings: National Academy Press, p. 54-74.

Dean, D.J., Topping, D.J., Schmidt, J.C., Griffiths, R.E., and Sabol, T.A., 2016, Sediment supply versus local hydraulic controls on sediment transport and storage in a river with large sediment loads: Journal of Geophysical Research—Earth Surface, v. 121, no. 1, p. 82-110, http://dx.doi.org/10.1002/2015JF003436.

Exner, F.M., 1920, Zur physik der dünen, Akad. der Wiss *in* Wien, Math-Naturwissenschafliche Klasse, Sitzungsberichte, Abt IIa, v. 134, n. 2a, p. 165-204.

Exner, F.M., 1925, Uber die wechselwirkung zwischen wasser und geschiebe in flüssen, Akad. der Wiss *in* Wien, Math-Naturwissenschafliche Klasse, Sitzungsberichte, Abt IIa, v. 134, p. 165-203.

Gloss, S.P., and Coggins, L.G., 2005, Fishes of the Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 33-56 p., http://pubs.usgs.gov/circ/1282/.

Gloss, S.P., and Coggins, L.G., 2005, Fishes of the Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 33-56 p., http://pubs.usgs.gov/circ/1282/.

Grams, P.E., Topping, D.J., Schmidt, J.C., Hazel, J.E., Jr., and Kaplinski, M.A., 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, no. 2, p. 361-381, http://dx.doi.org/10.1002/jgrf.20050.

Grams, P.E., Schmidt, J.C., Wright, S.A., Topping, D.J., Melis, T.S., and Rubin, D.M., 2015, Building sandbars in the Grand Canyon: EOS, v. 96, no. 11, p. 12-16, https://eos.org/features/building-sandbars-in-the-grand-canyon.

Griffiths, R.E., Topping, D.J., Andrews, T., Bennett, G.E., Sabol, T.A., and Melis, T.S., 2012, Design and maintenance of a network for collecting high-resolution suspended-sediment data at remote locations on rivers, with examples from the Colorado River: U.S. Geological Survey Techniques and Methods, book 8, chapter C2, 44 p., https://pubs.usgs.gov/tm/tm8c2/.

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.

Griffiths, R.E., and Topping, D.J., 2015, Inaccuracies in sediment budgets arising from estimations of tributary sediment inputs—An example from a monitoring network on the southern Colorado Plateau, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 583-594, https://acwi.gov/sos/pubs/3rdJFIC/Contents/4A-Griffiths.pdf.

Griffiths, R.E., and Topping, D.J., *in press*, Importance of measuring flow and sediment transport in ungaged tributaries when closing sediment budgets: Geomorphology.

Hall, R.O., Jr., Yackulic, C.B., Kennedy, T.A., Yard, M.D., Rosi-Marshall, E.J., Voichick, N., and Behn, K., 2015, Turbidity, light, temperature, and hydropeaking control primary productivity in the Colorado River, Grand Canyon: Limnology and Oceanography, v. 60, no. 2, p. 512-526, http://dx.doi.org/10.1002/lno.10031.

Howard, C.S., 1947, Suspended sediment in the Colorado River 1925-1941: U.S. Geological Survey Water-Supply Paper 998, 165 p., https://pubs.usgs.gov/wsp/0998/report.pdf.

McLean, S.R., 1992, On the calculation of suspended load for noncohesive sediments: Journal of Geophysical Research, v. 97, no. C4, p. 5759-5770, http://dx.doi.org/10.1029/91JC02933.

National Research Council, 1996, River resource management in the Grand Canyon: Washington, D.C., National Academy Press, Committee to review the Glen Canyon Environmental Studies, Water and Technology Board, Committee on Geosciences, Environment, and Resources, 226 p., http://www.nap.edu/catalog.php?record_id=5148.

Rubin, D.M., and Topping, D.J., 2001, Quantifying the relative importance of flow regulation and grain size regulation of suspended sediment transport α and tracking changes in bed sediment grain size β: Water Resources Research, v. 37, no. 1, p. 133-146, http://dx.doi.org/10.1029/2000WR900250.

Rubin, D.M., Tate, G.B., Topping, D.J., and Anima, R.A., 2001, Use of rotating side-scan sonar to measure bedload, *in* Seventh Federal Interagency Sedimentation Conference, Reno, Nev., March 25-29, 2001, Proceedings: Subcommittee on Sedimentation, v. 1, p. III-139 to III-143, http://walrus.wr.usgs.gov/reports/reprints/Rubin_FISC_7.pdf.

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, M., and Melis, T.S., 2002, Recent sediment studies refute Glen Canyon Dam hypothesis: Eos, Transactions, American Geophysical Union, v. 83, no. 25, p. 273, 277-278, http://dx.doi.org/10.1029/2002EO000191.

Rubin, D.M., and Topping, D.J., 2008, Correction to "Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport α, and tracking changes in bed-sediment grain size β": Water Resources Research, v. 44, no. W09701, p. 133-146, http://dx.doi.org/10.1029/2008wr006819.

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.

Schmidt, J.C., Rubin, D.M., and Ikeda, H., 1993, Flume simulation of recirculating flow and sedimentation: Water Resources Research, v. 29, no. 8, p. 2925-2939, http://dx.doi.org/10.1029/93WR00770.

Schmidt, J.C., and Grams, P.E., 2011, The high flows—Physical science results, *in* Melis, T.S., ed., Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, p. 53-91, http://pubs.usgs.gov/circ/1366/.

Sibley, D., Topping, D.J., Hines, M., and Garner, B., 2015, User-interactive sediment budgets in a browser—A web application for river science and management, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 595-605, https://acwi.gov/sos/pubs/3rdJFIC/Contents/4A-Sibley.pdf.

Sibley, D., Topping, D.J., Hines, M., and Garner, B., 2015, User-interactive sediment budgets in a browser—A web application for river science and management, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 595-605, https://acwi.gov/sos/pubs/3rdJFIC/Contents/4A-Sibley.pdf.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport—1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515-542, http://dx.doi.org/10.1029/1999WR900285.

Topping, D.J., Rubin, D.M., Nelson, J.M., and Kinzel, P.J., 2000, Colorado River sediment transport—2. Systematic bed-elevation and grain-size effects of sand supply limitation: Water Resources Research, v. 36, no. 2, p. 543-570, http://dx.doi.org/10.1029/1999WR900286.

Topping, D.J., Schmidt, J.C., and Vierra, L.E., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona: May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p., http://pubs.water.usgs.gov/pp1677/.

Topping, D.J., Rubin, D.M., and Melis, T.S., 2007, Coupled changes in sand grain size and sand transport driven by changes in the upstream supply of sand in the Colorado River—Relative importance of changes in bed-sand grain size and bed-sand area: Sedimentary Geology, v. 202, no. 3, p. 538-561, http://dx.doi.org/10.1016/j.sedgeo.2007.03.016.

Topping, D.J., Rubin, D.M., Grams, P.E., Griffiths, R.E., Sabol, T.A., Voichick, N., Tusso, R.B., Vanaman, K.M., and McDonald, R.R., 2010, Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010-1128, 111 p., http://pubs.usgs.gov/of/2010/1128/.

Topping, D.J., Rubin, D.M., Wright, S.A., and Melis, T.S., 2011, Field evaluation of the error arising from inadequate time averaging in the standard use of depth-integrating suspended-sediment samplers: U.S. Geological Survey Professional Paper 1774, 95 p., http://pubs.usgs.gov/pp/1774/pp1774.pdf.

Topping, D.J., and Wright, S.A., 2016, Long-term continuous acoustical suspended-sediment measurements in rivers—Theory, application, bias, and error: U.S. Geological Survey Professional Paper 1823, 98 p., http://dx.doi.org/10.3133/pp1823.

Topping, D.J., Wright, S.A., Griffiths, R.E., and Dean, D.J., 2016, Long-term continuous acoustical suspended-sediment measurements in rivers—Theory, evaluation, and results from 14 stations on five rivers *in* Constantinescu, G., Garcia, M., and Hanes, D., eds., River Flow 2016, Proceedings of the International Conference on Fluvial Hydraulics, Iowa City, Mo., July 11-14, 2016: CRC Press, p. 1510-1518, http://www.crcnetbase.com/doi/abs/10.1201/9781315644479-238.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam, Colorado River storage project, Arizona—Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, 337 p. plus appendices, http://www.usbr.gov/uc/envdocs/eis/gc/gcdOpsFEIS.html.

U.S. Department of the Interior, 2011, Environmental assessment—Development and implementation of a protocol for high-flow experimental releases from Glen Canyon Dam, Arizona, 2011 through 2020: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 176 p. plus appendices, http://www.usbr.gov/uc/envdocs/ea/gc/HFEProtocol/HFE-EA.pdf.

U.S. Department of Interior, 2016a, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

U.S. Department of Interior, 2016b, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Geological Survey, 2017, Discharge, sediment, and water quality monitoring, available at https://www.gcmrc.gov/discharge_qw_sediment/.

Vernieu, W.S., Hueftle, S.J., and Gloss, S.P., 2005, Water quality in Lake Powell and the Colorado River, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 69-85 p., http://pubs.usgs.gov/circ/1282/.

Voichick, N., 2008, Specific conductance in the Colorado River between Glen Canyon Dam and Diamond Creek, Northern Arizona, 1988-2007: U.S. Geological Survey Data Series 364, 16 p., http://pubs.usgs.gov/ds/364/.

Voichick, N., and Wright, S.A., 2007, Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, northern Arizona, 1988-2005: U.S. Geological Survey Data Survey Series 251, 24 p., http://pubs.usgs.gov/ds/2007/251/.

Voichick, N., and Topping, D.J., 2010, Use of specific conductance in estimating salinity and as a natural tracer of water parcels in the Colorado River between Glen Canyon Dam and Diamond Creek, Northern Arizona, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18-20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010-5135, 343-46 p., http://pubs.usgs.gov/sir/2010/5135/.

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://dx.doi.org/10.3133/sir20145097.

Voichick, N., Kennedy, T.A., Topping, D.J., Griffiths, R.E., and Fry, K., 2016, Water clarity of the Colorado River—Implications for food webs and fish communities: U.S. Geological Survey Fact Sheet 2016-3053, 4 p., http://dx.doi.org/10.3133/fs20163053.

Wiele, S.M., and Griffin, E.R., 1998, Modifications to a one-dimensional model of unsteady flow in the Colorado River through Grand Canyon, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97-4046, 17 p., https://pubs.usgs.gov/wri/1997/4046/report.pdf.

Wiele, S.M., and Smith, J.D., 1996, A reach-averaged model of diurnal discharge wave propagation down the Colorado River through the Grand Canyon: Water Resources Research, v. 32, no. 5, p. 1375-1386, http://dx.doi.org/10.1029/96WR00199.

Wright, S.A., Melis, T.S., Topping, D.J., and Rubin, D.M., 2005, Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand

Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, p. 17-31, http://pubs.usgs.gov/circ/1282/.
Wright, S.A., Schmidt, J.C., Melis, T.S., Topping, D.J., and Rubin, D.M., 2008, Is there enough sand? Evaluating the fate of Grand Canyon sandbars: GSA Today, v. 18, no. 8, p. 4-10, http://dx.doi.org/10.1130/GSATG12A.1.
Wright, S.A., Anderson, C.R., and Voichick, N., 2008, A simplified water temperature model for the Colorado River below Glen Canyon Dam: River Research and Applications, v. 25, no. 6, p. 675-686, http://dx.doi.org/10.1002/rra.1179.
Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., 2010, An approach for modeling sediment budgets in supply-limited rivers: Water Resources Research, v. 46, no. W10538, p. 1-18, http://dx.doi.org/10.1029/2009WR008600.
Wright, S.A., and Kennedy, T.A., 2011, Science-based strategies for future high-flow experiments at Glen Canyon Dam, *in* Melis, T.S., ed., Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, p. 127-147, http://pubs.usgs.gov/circ/1366/.

7. Budget

Project	Project Description	Fiscal Year 2018 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$146,500	$2,000	$5,000	$29,000		$183,609	$28,392	$394,501
A.2	Water quality	$82,200	$2,000	$20,000	$29,000		$54,200	$20,722	$208,122
A.3	Sediment transport and budgeting	$302,900	$6,000	$55,000	$29,000		$173,000	$61,123	$627,023
	Total A	**$531,600**	**$10,000**	**$80,000**	**$87,000**	**$0**	**$410,809**	**$110,237**	**$1,229,646**

Project	Project Description	Fiscal Year 2019 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$150,900	$2,000	$5,100	$29,600		$186,600	$48,776	$422,976
A.2	Water quality	$84,700	$2,000	$10,200	$29,600		$55,300	$32,890	$214,690
A.3	Sediment transport and budgeting	$255,050	$6,100	$56,100	$29,600		$176,400	$90,181	$613,431
	Total A	**$490,650**	**$10,100**	**$71,400**	**$88,800**	**$0**	**$418,300**	**$171,847**	**$1,251,097**

Project	Project Description	Fiscal Year 2020 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$155,400	$2,100	$5,200	$30,200		$190,300	$50,154	$433,354
A.2	Water quality	$87,300	$2,100	$10,200	$30,200		$56,400	$33,748	$219,948
A.3	Sediment transport and budgeting	$291,050	$6,200	$57,200	$30,200		$179,900	$100,009	$664,559
	Total A	**$533,750**	**$10,400**	**$72,600**	**$90,600**	**$0**	**$426,600**	**$183,911**	**$1,317,861**

8. Experimental Project Budget (see Appendix 2e)

Minor supplemental funding may be requested to cover additional salary, logistics, and travel for extended fieldwork in order to conduct additional monitoring and research during special LTEMP flow experiments (e.g., extended-duration HFEs). The costs for this experimental work are estimated to be no more than $15,000 to $20,000 per special LTEMP experiment.

9. Elements and Activities Proposed, but not Included in the Final Work Plan

Reductions of funding in FY19 and FY20 will require a rearrangement in the scope of the water-quality work. Some of the water-quality monitoring downstream from Lees Ferry may be reduced or some gaging stations may be discontinued.

Project B. Sandbar and Sediment Storage Monitoring and Research

1. Investigators

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2. Project Summary

The purposes of this project are to a) track the effects of individual HFEs on sandbars, b) monitor the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics.

The sand deposits on the bed and banks of the Colorado River in Glen, Marble, and Grand Canyons are directly affected by the operations of GCD. Depending on the relative magnitudes of dam releases and tributary sediment inputs, sand either accumulates or is eroded from the bed of the river. When evaluated over long river reaches, sand is evacuated from the river bed during sustained periods of high dam-releases (Topping and others, 2000; Grams and others, 2015) and sand accumulates during periods of average dam-releases and substantial tributary sediment inputs (Grams, 2013; Grams and others, 2013). Sandbars along the river banks above average base flow (about 8,000 ft^3/s) also change in response to dam operations, but in a different pattern, because they are not always inundated and because they comprise a small fraction of the sand in the system (Hazel and others, 2006; Grams and others, 2013). These deposits aggrade significantly during HFEs that exceed powerplant capacity (Schmidt and Grams, 2011) and, to a lesser extent, during powerplant capacity flows (Hazel and others, 2006). These deposits typically erode during normal powerplant operations between HFEs (Hazel and others, 2010).

One of the stated goals in the ROD for the recently completed LTEMP (U.S. Department of the Interior, 2016) is to "increase and retain fine sediment volume, area, and distribution...for ecological, cultural, and recreational purposes." Expectations of improved sandbar building and conservation of sediment were among the criteria used in the selection of the preferred alternative. One of the central components of the selected alternative is the continued implementation of HFEs for building sandbars. The LTEMP extends the program initiated with the Environmental Assessment for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam (HFE Protocol) which asked the question, "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? Additional, condition-dependent experiments are included in the preferred alternative, with objectives related to sandbar building and sediment conservation. Project B includes elements that are designed to evaluate whether the sediment-related goals of the LTEMP are met, provide the information that is needed to proceed with or abort LTEMP experimental activities, and evaluate the effectiveness of implemented experiments.

Thus, one of the most important objectives of Project B 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. The monitoring program described here continues the program implemented in previous work plans 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. These annual measurements and daily photographs are included in Project Element B.1. This project element also includes work to more efficiently conduct quantitative analyses of the remote camera images. Because these long-term monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, Project Element B.2 includes periodic measurements of nearly all sandbars within individual 50 to 130 km sediment budget reaches (see Project A for description of sediment budget reaches).

Another critical piece of information that is needed to evaluate the outcome of the HFE Protocol and the LTEMP is the change in total sand storage in long river reaches. 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 deposition is the sand that is in storage on the channel bed, which is the sum of the sand contributed by the most recent tributary inputs, any sand that may have accumulated since GCD 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 the quantity of sand most recently contributed by the Paria River, thereby preventing depletion of pre-dam era sand. Some of the sand mobilized by HFEs is deposited in eddies where it builds eddy sandbars.

Some of the sand is eventually transported downstream to Lake Mead. The most efficient floods for the purposes of sandbar building are those that maximize 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. Sediment delivered by the LCR also contributes to sand storage downstream from the LCR confluence. However, this tributary has contributed only a small fraction of the quantity of sand delivered by the Paria River (Griffiths and Topping, 2015) and is not included in the HFE protocol.

Measured trends in sand storage along the channel bed combined with trends in exposed sandbars will provide the necessary context on which to base future decisions about dam operations and other potential management options. If sand storage is maintained or increased, we expect the response to future HFEs to be similar to or better than that observed following recent HFEs. In contrast, depletions of fine sediment in the active channel are potentially irreversible if sand supply from tributaries is consistently less than downstream transport. This situation would threaten the long-term ability to maintain eddy sandbars. These long-term trends are measured in Project Element B.2, which includes one "channel mapping" campaign to map changes in sand storage in both lower Marble Canyon (RM 30-61) and eastern Grand Canyon (RM 61-87) in 2019. Because these sediment-budget reaches have been mapped previously and because mapping efficiency has increased, we are able to map longer river reaches in a single river trip than previously. These data will be used to provide long-term (8 to 10 year) assessments of sandbar and sand storage change for these reaches and a robust evaluation of 7 years of implementation of the HFE Protocol. Project Element B.3 includes work to improve the control network in support of this and other work plan projects, with focus on the segment between RM 87 and RM 166, which has never been mapped. The control work is needed to prepare for mapping this segment in the next (FY2021-23) work plan.

This project also includes one element that provides contingency data collection for HFE experiments. Project Element B.4 describes studies that will be conducted to monitor and evaluate the condition-dependent experiments that affect sandbars and sediment resources. This work plan also includes description of two research components that, because of budget constraints, were not funded. Project Element B.5 describes a modeling project to produce flow models that predict the inundation extent and flow velocities for dam operations and HFEs in Marble Canyon and improve capabilities for predicting sandbar response to dam operations. The modeling project element also includes description of proposed laboratory experiments to address the same suite of questions as the condition-dependent experimental HFEs are designed to test. Project Element B.6 is a research project that proposes to investigate river channel adjustment and redistribution of reservoir delta sediment on the Colorado River within the CRe between Diamond Creek and the western boundary of Grand Canyon National Park.

3. Hypotheses and Science Questions

Sediment-related goals of the GCDAMP have been articulated in strategic science plans (2003), knowledge assessment workshops (2005 and 2012), and statements of desired future conditions (2011). Common among these are goals to “maintain” and “enhance” sandbars, camping beaches, and nearshore habitats. Similarly, the sediment-related goal stated in the LTEMP EIS is to “increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.” The HFE Protocol EA asks, "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?

The goals described above guide the development of the following set of hypotheses and science questions addressed in Project B:

1) **Hypothesis: Sandbars will increase in size.** What is the long-term effect of dam operations, including HFEs, on the distribution, abundance, and size of eddy sandbars? 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? This provides information needed by managers to decide whether to continue with planned experimental flows (HFEs), whether to use an “off-ramp” to postpone or discontinue experimental flows, and whether to consider other management options. *Addressed in Project Elements B.1 and B.2.*
2) **Hypothesis: Sand storage will increase.** What is the long-term effect of dam operations, including HFEs, on the amount of fine sediment stored in the active channel at all elevations? What are the implications of these changes for the continued use of HFEs to build sandbars? These changes are relevant to eddy sandbars, backwaters and other aquatic habitat, and the relative partitioning of transported sediment into eddies and downstream, which ultimately determines whether the use of experimental high flows is sustainable and whether changes in dam operations or other management actions should be considered. *Addressed in Project Element B.2.*
3) **Hypothesis: Future HFEs will have same effect as past HFEs.** 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? *Addressed in Project Elements B.1, B.2, B.4, and B.5 (unfunded).*

4) **Hypothesis: Longer duration HFEs result in more deposition.** How does variation in HFE magnitude, duration, and ramp rate affect sandbar response? (Are extended-duration HFEs and spring proactive HFEs effective?) *Addressed in Project Element B.4 (if extended duration HFE occurs) and Project Element B.5 (unfunded).*
5) **Hypothesis: Larger magnitude HFEs result in larger sandbars.** How does variation in HFE magnitude, duration, and ramp rate affect sandbar response? (Are extended-duration HFEs and spring proactive HFEs effective?) *Addressed in Project Element B.5 (unfunded).*
6) **Hypothesis: Lower HFE downramp rate results in sandbars with gentler slopes.** How does variation in HFE magnitude, duration, and ramp rate affect sandbar response? (Are extended-duration HFEs and spring proactive HFEs effective?) *Addressed in Project Element B.5 (unfunded).*
7) **Hypothesis: Bank erosion in the western Grand Canyon has increased as a result of Lake Mead drawdown.** What are the rates and spatial patterns of bank erosion and bed sedimentation in the now riverine segment of the Lake Mead Delta? *Addressed in Project Element B.6 (unfunded).*
8) **Hypothesis: The river bed in western Grand Canyon is aggrading.** If the bed is aggrading, what is the relative role of sediment contributed by bank erosion, sediment influx from upstream, and the existence of Pearce Ferry rapid as a downstream nickpoint? What would be the effect of erosion of or removal of Pearce Ferry rapid? *Addressed in Project Element B.6 (unfunded).*
9) **Hypothesis: Bedload sand transport can be predicted as a function of suspended sand transport.** Can we improve reach-scale estimates of sand flux and sediment mass balance by better quantifying the contribution of bedload transport? *Addressed in Project Element B.2 (unfunded).*
10) **Hypothesis: Annual changes in sand storage are a small fraction of total active sand storage.** How much sand remains in active storage in eddies and on the bed of the river in Marble Canyon and Grand Canyon? Is this amount small or large relative to the measured changes in storage? This provides context for predicting the continued effectiveness of HFEs for building sandbars. *Addressed in Project Element B.2 (unfunded).*

4. Background

The changes to the flow regime and sediment supply associated with completion of GCD (Topping and others, 2000) caused deep scour and armoring of the river bed between the dam and Lees Ferry, 25 km downstream (Pemberton, 1976; Williams and Wolman, 1984; Grams and others, 2007). Downstream from Lees Ferry in Marble and Grand Canyons, the debris fans at tributary mouths result in a different channel configuration and different style of response to the upstream dam. The boulder and cobble deposits that form rapids have been largely stable (Magirl and others, 2005), while areas of the bed covered by fine sediment have been eroded, and many eddy sandbars are much smaller than they once were (Schmidt and others, 2004; Wright and others, 2005). Because systematic measurements of fine-sediment thickness have not yet been made, the total volume of fine sediment present (or eroded) in Marble and Grand Canyons is not known.

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

$$I - O = \Delta S, \qquad (1)$$

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 reach 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 occasionally inundated. Thus,

$$\Delta S = \Delta S_{low} + \Delta S_{high}. \qquad (2)$$

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 are the source for sand remobilized during HFEs. The high-elevation fine-sediment deposits are alternately inundated and exposed, depending on the flow regime. These deposits are used as camping beaches, support riparian vegetation, and support other upland resources.

Annual monitoring of high-elevation deposits has been conducted systematically since 1990. These data clearly demonstrate the role of dam operations, primarily HFEs, in causing changes in sandbar size (Fig. 1). Each HFE has resulted in deposition and there has been erosion in each of the periods between HFEs (Hazel and others, 2010; Schmidt and Grams, 2011; Mueller and others, 2014). HFEs conducted within the HFE Protocol since 2012 have resulted in sustained, but not progressive, increases in sandbar area. Additionally, vegetation has established on portions of sandbars in many parts of the river corridor since the beginning of monitoring (Sankey and others, 2015; Mueller and others, 2016), which may stabilize new HFE deposits so that the extent to which deposition causes increases in the area of exposed bare sand actually decreases.

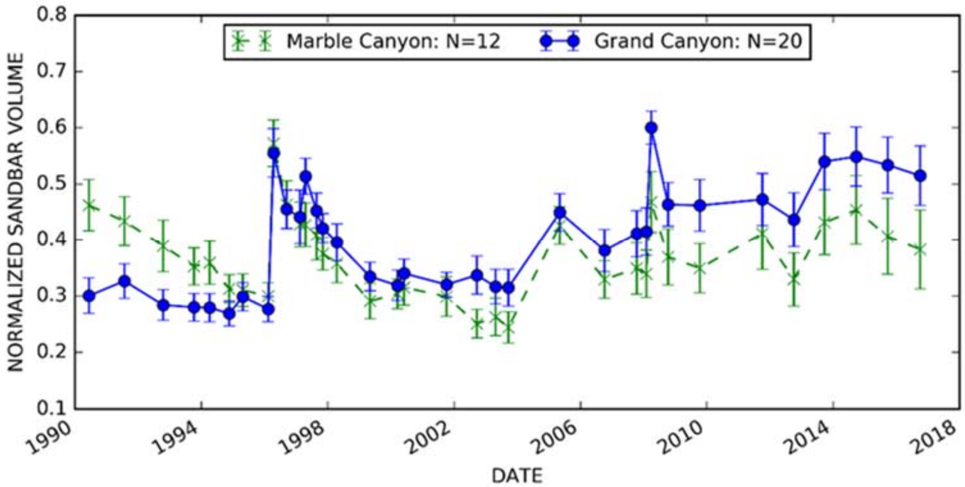

Figure 1. Sandbar size from 1990 to October 2016 (preliminary data provided by Joseph E. Hazel, Jr.). N is the number of sites in those respective reaches. The sandbar volume is normalized to the maximum expected volume for each site.

Low- and high-elevation deposits are coupled through processes of streamflow erosion and deposition, wind erosion and deposition, and mass failure. This coupling means that changes in ΔS will affect both low- and high-elevation sediment. Although HFEs are scheduled based on the quantity of recent sand inputs from the Paria River, both those inputs and residual sand are mobilized to elevate sand concentrations. Recent investigations of the geochemistry of sand deposited during HFEs indicates that between 20% and 80% of the sand within HFE deposits is likely derived from the Paria River (Chapman and others, 2016), with the remainder derived from pre-dam sediment from the channel and its margins. Thus, a substantial proportion of the sand deposited during HFEs may be derived from background sand storage – the pre-dam sediment stored in eddies and the riverbed. Because higher concentrations of sand in suspension will result in greater rates of deposition during HFEs (Wiele and others, 1999), decreases in background sand storage – unless they are offset by tributary sediment inputs – will likely lead to diminished capacity to achieve one of the central LTEMP goals of rebuilding and maintaining sandbars using HFEs. Therefore, predictions about the long-term fate of sandbars must be based on understanding long-term trends in ΔS, including both ΔS_{low} and ΔS_{high}. For these reasons, the sandbar research and monitoring is designed around this concept of the sediment budget.

The measurements of suspended sediment made in Project A track the inputs and outputs (I and O in equation (1) and are used to calculate ΔS for the sediment budget reaches[2]. This approach

[2] In this proposal, 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

tracks the accumulation of tributary inputs that is essential for implementation of the HFE Protocol. However, this calculation does not distinguish between low- and high-elevation deposits. Consequently, equation (1) alone cannot be used to evaluate changes in sandbar size, campsite area, sand available for plant colonization, or other changes of recreational or ecological significance. Uncertainty in the measurements of total sediment flux also accumulate with time, limiting the utility of those measurements for tracking long-term trends.

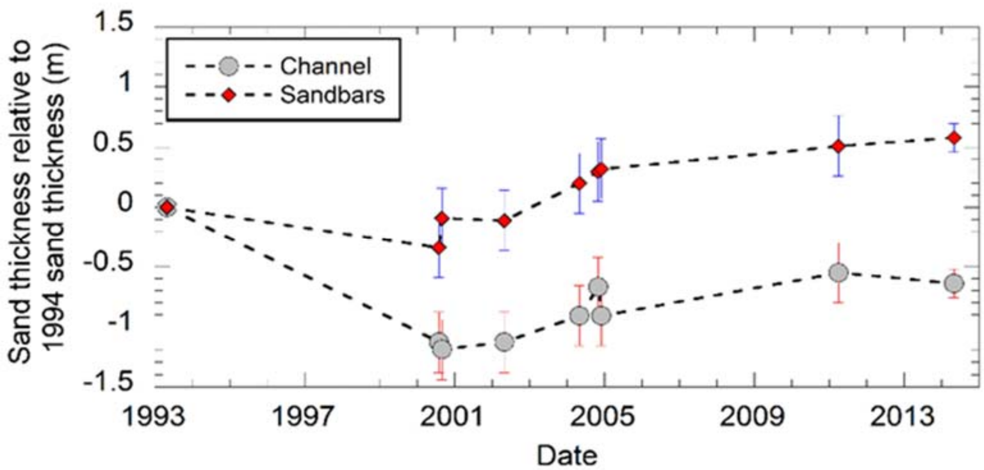

Figure 2. Change in mean bed elevation between 1993 and 2011 for a 4-km reach between RM 63 and RM 65 in eastern Grand Canyon. The changes between 2011 and 2014 are based on measurements made throughout all of eastern Grand Canyon and have less uncertainty. Uncertainty is a smaller fraction of the change in this example than in Fig. 3, because this figure shows larger changes over a longer time period.

Previous studies analyzing repeat topographic measurements of the channel, eddies, and sandbars have found that 90% or more of the changes in sand volume occur at low-elevation, and that high-elevation sandbars comprise only about 10% or less of the fine sediment in the system (Hazel and others, 2006). These studies have also found that ΔS computed for short study reaches yielded different values than ΔS computed as the difference between sand inflows measured at gaging stations using equation (1). This discrepancy stems from the inability to correctly extrapolate measurements from the short reaches to larger spatial scales because changes in bed topography are highly localized and spatially variable (Grams and others, 2013). These findings demonstrate that determining whether sediment storage in each storage environment – at low and high elevations and in the channel and eddy – is increasing, decreasing, or stable, requires repeat measurements of sand storage in a large sample of the storage environments within each of the long sediment-budgeting reaches.

on the order of 2 to 5 km in length. We use “long reach” or “sediment budgeting reach” to refer to reaches of the river that encompass the entire channel between fine-sediment monitoring gages; these reaches are 50 to 130 km in length.

Such measurements have been made in some of the sediment-budgeting reaches since 2009 and repeat maps for lower Marble Canyon and eastern Grand Canyon both capture large spatial variability in erosion and deposition that allow robust calculation of the evacuation of sand that occurred during the period of high releases in summer 2011 (Grams and others, 2015). These measurements also show an overall loss of high-elevation sand in lower Marble Canyon and a slight increase in high-elevation sand in eastern Grand Canyon.

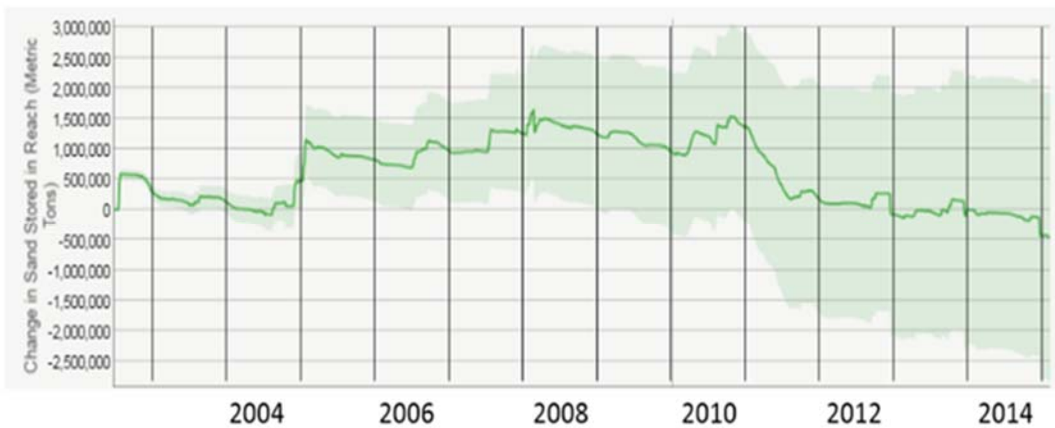

Figure 3. Sand budget for August 2002 to December 2014 for eastern Grand Canyon. The sand budget computed by the difference in sand transport at the upstream and downstream ends of the reach is shown by the solid line with the shaded region indicating uncertainty bounds.

As the period of repeat measurement of the bed and sandbars lengthens, the value of those measurements and the importance of the interpretations will increase. Figure 2 shows changes in bed elevation for a 4-km reach between RM 63 and RM 65 between 1993 and 2014. For the period between 2002 and 2014, these data show changes that are consistent with the flux-based sand budget but have much less uncertainty than the flux-based measurements (Fig. 3) whose uncertainty accumulates with time.

Figure 4 illustrates how these measurements will be interpreted and how they may be used to guide management decisions. This plot shows sand thickness change in sandbars (⟦ΔS⟧_high) against sand thickness change in the eddy and channel (⟦ΔS⟧_low), using all of the data collected in lower Marble Canyon (changes between 2009 and 2012) and eastern Grand Canyon (changes between 2011 and 2014). The measurements for individual eddies show a general tendency for the low- and high-elevation deposits to change similarly, but there are many eddies for which the low and high elevation deposits change in opposing directions. Averaged for all of lower Marble Canyon, there was erosion of both low- and high-elevation deposits. On average in eastern Grand Canyon, there was erosion of low-elevation deposits and slight deposition of high-elevation deposits. If sustained over long periods, these changes would have significant management implications.

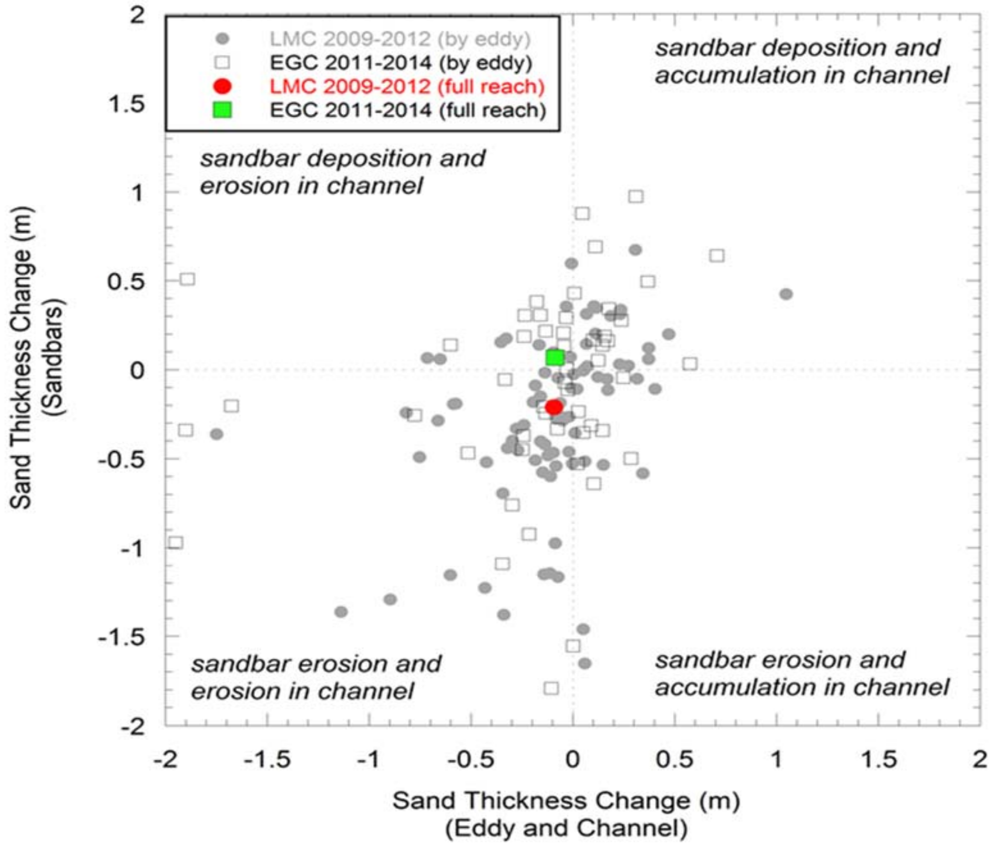

Figure 4. Change in high-elevation sand (sandbars) as a function of change in low-elevation sand (eddy and channel) based on repeat measurements in lower Marble Canyon and eastern Grand Canyon (EGC). The data points "by eddy" show changes tabulated for each eddy within the respective reaches. The colored "full reach" points show the average of all changes for each reach. Changes are in average "thickness" of sand. An average thickness change of just 0.5 m over a 50-km reach equates to over 4 million metric tons of sand.

Sandbar deposition accompanied by accumulation in the channel would indicate that sandbar building and sediment conservation goals are likely being met and, furthermore, that sand supply would likely support increases in HFE frequency and/or duration. Sandbar erosion accompanied by sand accumulation in the channel would also indicate that despite adequate sand supply, sandbar maintenance goals are not being met. This would suggest some change in operations might be required to achieve different results. Sandbar deposition accompanied by erosion in the channel is expected to occur over short periods (such as during HFEs) as sand is transferred from low to high elevation. However, continuation of this pattern over long periods would indicate that sandbars are being built at the expense of progressive depletion from the channel. In this case, reductions in HFE frequency and duration or other changes to operations might be considered. The "worst case" scenario is sandbar erosion accompanied by erosion in the channel. This is also expected to occur over short time periods, but over long periods would likely indicate that available sand supply is insufficient to support sandbar maintenance without changes in dam operations or other management actions. In summary, if sandbar maintenance goals are not being met and information on low-elevation sand storage is not available, the cause of sandbar declines will be uncertain making it difficult to identify the best management response.

5. Proposed Work

5.1. Project Elements

Project Element B.1. Sandbar monitoring using topographic surveys and remote cameras

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Project Description

The primary purpose of the sandbar monitoring project is to track the individual and cumulative effects of HFEs and intervening dam operations on sandbars and campsites in the CRe. In addition, this project will evaluate how sandbar size and shape; 1) affect the bar-building response of HFEs, and 2) affect bar erosion following HFEs.

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 sandbar time-series, which is maintained in cooperation with Northern Arizona University and is the longest, most accurate, and complete dataset describing the state of sandbars in the CRe. The sandbar data and visualization tools are available online at www.gcmrc.gov/sandbar. 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. Methods for these surveys are described by Hazel and others (2008; 2010) and Kaplinski and others (2009; 2014). These annual surveys are supplemented by photographs of 42 sites, taken five or more 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. The FY2015–17 work plan included a project that evaluated using images collected from hand-held and pole mounted digital cameras for surveying sandbars. The project demonstrated that the method can be applied to surveying sandbars, but does not provide a time or cost savings over the traditional methods. Therefore, we do not propose a change in monitoring methods for this work plan.

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 is 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 within a collection protocol by Grand Canyon River Guides through the "Adopt-a-Beach" program.

During the FY2015-17 work plan, techniques were developed and tested for using the remote camera images to: 1) compute sandbar area; 2) estimate sandbar face slope in the region of flow fluctuations; and 3) estimate sandbar volumes from digital elevation models (DEMs) of entire sandbars from photographs taken during the recession phase of an HFE. During the next work plan, we propose to move beyond this 'proof-of-concept' phase into a robust monitoring technique that will be implemented at 10 to 15 of the existing network of 45 sites to reliably provide: 1) monthly time-series of sandbar areas and face slopes, and 2) sandbar volume immediately after HFEs.

A monthly time-series of sandbar area and shoreface slope measurements will provide crucial and otherwise unobtainable information about the retention of sand in bars in the months following HFEs as well as in response to equalization flows and other proposed flows. Sandbar volume estimates derived from measurements made immediately following HFEs will provide the necessary data to quantify and understand the HFE response of a given sandbar, and a set of sandbars collectively. Furthermore, the greater temporal resolution of the sandbar time-series will allow for a more robust quantification of sandbar erosion rates following HFEs. This will be a major advance over present qualitative (visual) assessments of sandbar responses to HFEs, and will be vital to model validation in Project Element B.5 (unfunded).

There are three major aspects to computing a time-series of sandbar area measurements from a series of oblique photographs at a site. First, the image must be georectified (Fig. 5), which is the process of creating a planform-perspective image in a projected coordinate system. Second, the sandbar must be segmented from the image, which is the process of identifying the entire outline of the sandbar. Third, relationships must be established between the area of a sandbar at a given time (i.e., at a specific flow stage), and that at a reference flow stage (8,000 ft^3/s), for comparative purposes.

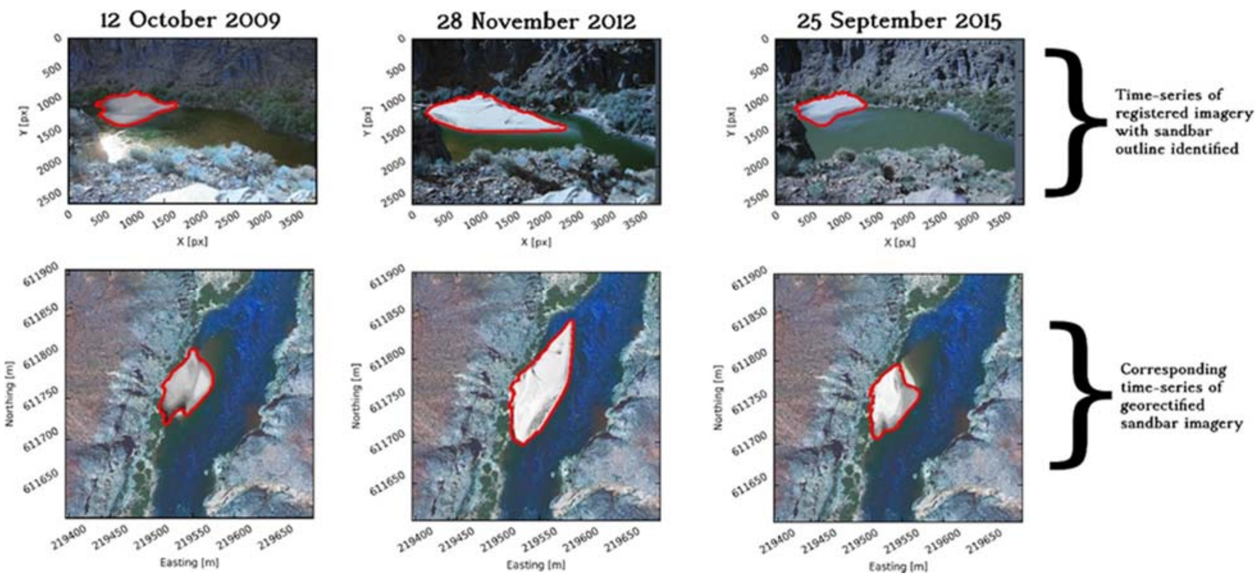

Figure 5. Time-series of registered oblique (top row) and corresponding georectified (bottom row) imagery. The red perimeters of the bar have been found using a semi-automated procedure.

To facilitate data processing and analysis, we intend to develop software that will be linked to a database that will streamline the entire processing workflow. This workflow includes image uploading, keeping track of image metadata and derived data from images, implementing methods for image registration, georectification, segmentation, extraction of waterline contours, area and slope estimation, post-flood DEM construction and sandbar volume estimation. Each step will be automated to the greatest extent possible. Recent evaluation of machine learning algorithms, indicates it may be possible to make the sandbar segmentation process fully automated. We are working on a promising new image segmentation algorithm using a probabilistic graphical model fed by sparse feature labeling using a conditional neural network (one of a class of algorithms called 'deep learning') trained on a subset of the remote camera imagery. This open-source software will serve as the 'one-stop' sandbar-monitoring tool that will store data in formats that can easily be served on the existing sandbar-monitoring website and data repository at www.gcmrc.gov/sandbar.

Outcomes and Products

- Update on sandbar area and volume and campsite area based on monitoring from the previous year. This information will be provided annually at the Annual Reporting Meeting each January and as requested.
- Annual monitoring data made available on website (www.gcmrc.gov/sandbar) within six months following data collection.
- Adopt-a-Beach photography to be served on website on an annual basis (www.gcmrc.gov/sandbar).

- Remote camera images showing effects of HFEs made available on website within two months following data collection (www.gcmrc.gov/sandbar).
- Remote camera image georectifications, sandbar area and slope time-series, and post-HFE sandbar volumes, for at least 13 sites, also served on sandbar website (www.gcmrc.gov/sandbar).
- Report and/or journal article describing remote camera image processing methods and results.

Project Element B.2. Bathymetric and topographic mapping for monitoring long-term trends in sediment storage[3]

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Project Description

LTEMP objectives for fine sediment are focused on the condition of sandbars. The purpose of the HFE protocol embedded in the LTEMP is to maintain and build sandbars using high flow releases that are timed to coincide with periods of sand supply from tributaries (Wright and Kennedy, 2011). The success of this approach is predicated on the existence of sand within the channel for rebuilding sandbars. The primary purpose of Project Element B.2 is to track trends in sandbar conditions and sand storage over the time scale of the HFE protocol and the LTEMP and thereby provide a robust measure of whether or not that supply of sand (the sum of recent tributary inputs and background storage) necessary for building sandbars is increasing, decreasing, or stable (Wright and others, 2008). This project monitors changes in sand storage by location, providing spatially explicit quantification of changes in the channel, eddies and sandbars. The results from this project will be used to evaluate the outcome of the flow regime adopted in the LTEMP with respect to sandbar building and sand conservation.

The measurements of sand storage in the channel are critical, because that information will be needed to explain the observed trends in sandbar area and volume. This information will be needed to determine whether HFEs should be conducted more frequently or less frequently than

[3] Project Element B.2 was partially cut to meet budget. See B.i. in Section 9.

prescribed in the LTEMP ROD and will be needed to assess whether the implemented flow regime alone is sufficient to achieve sediment-related goals, or whether additional management actions should be considered.

The sampling design used in this project is based on our current understanding of sediment dynamics, the locations of stream-gaging stations, and the timeframe of the LTEMP. The CRe is divided into seven sediment-budget reaches based on the location of the streamflow and sediment gages (Table 1). For each of the five reaches between Lees Ferry and Diamond Creek, flux-based sand budgets are computed at 15-min. intervals (see Project A). In using these same reach boundaries for long-term sandbar and sand-storage monitoring, we are able to correlate changes that occur in the channel, eddies, and on sandbars with the measurements of sand transport. Because erosion and deposition are spatially variable (Grams and others, 2013), it is necessary to measure approximately 50% to 70% of the channel and eddies within each of these reaches to ensure that the signal in sand-storage change is greater than the "noise" caused by that spatial variability (Grams and others, 2015). Because about 90% of the sand that is available for redistribution by dam operations is submerged (Hazel and others, 2006), the monitoring method must include measurements of sediment on the bed of the river in eddies and pools. Bed sediment 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; 2010) and Kaplinski and others (2009; 2014; 2017). The data will result in high-resolution DEMs of the mapped reaches for each mapping effort (e.g. Kaplinski and others, 2017).

The proposed schedule for completing repeat maps for each reach is based on the major milestones in the high-flow experimental protocol (implemented in 2012) and the LTEMP. These milestones are; 1) 10 years of implementing the HFE protocol, 2) 10 years after LTEMP implementation when a major evaluation is required, and 3) 20 years after LTEMP implementation. The assessment of the first 10 years of the HFE protocol will be based on repeat maps of lower Marble Canyon and eastern Grand Canyon that will be collected in this work plan (the data will be collected in 2019 so that a report will be available by 2020). Upper Marble Canyon is not included in this assessment in an effort to limit mapping frequency to one data collection effort in this 3-year work plan to provide the flexibility that will be required to implement the contingency studies to evaluate the effects of LTEMP experimental flows (see Project Element B.4). The 10-year assessment of LTEMP will be provided by repeat maps of upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon conducted between 2023 and 2025. Repeat maps of west-central Grand Canyon and east-central Grand Canyon will be completed in 2027 and 2028, respectively, to provide interim evaluations of the effects of LTEMP operations on those reaches. The final assessment of LTEMP will be based on repeat maps of all reaches conducted between 2032 and 2036.

Efforts are focused on Marble Canyon and eastern Grand Canyon, because these reaches are believed to have the greatest risk of sediment deficit and because sandbar volume gains in the HFE period since 2012 implementation of the HFE protocol have not been as large in Marble Canyon as in downstream reaches. However, exclusive focus on Marble Canyon does not fully address sediment-related GCDAMP and LTEMP goals, which include all river reaches in the CRe. For these reasons, an initial map of west-central Grand Canyon was completed in April 2017. We propose completing an initial map of east-central Grand Canyon in FY2021, which will require control work in the current work plan (see Project Element B.3). This schedule reduces field activities to one or two mapping campaigns in each three-year work plan.

Table 1. Proposed schedule of channel mapping efforts for this work plan through the period of the LTEMP.

Segment	River Miles	Completed surveys	Planned surveys	Repeat interval
1) Glen Canyon	-15 to 0	2000, 2015	2023, 2033	7 to 10 yr
2) Upper Marble Canyon	0 to 30	2013, 2016	2023, 2033	7 to 10 yr
3) Lower Marble Canyon	30 to 61	2009, 2012	2019, 2024, 2032	5 to 8 yr
4) Eastern Grand Canyon	61 to 87	2011, 2014	2019, 2025, 2032	5 to 8 yr
5) East-central Grand Canyon	87 to 166	none	2021, 2028, 2035	7 to 10 yr
6) West-central Grand Canyon	166 to 225	2017	2027, 2034	7 to 10 yr
7) Western Grand Canyon	225 to 280	none	*research only	

Because field work is not proposed for 2018, that year will be used for analysis and reporting of data collected in 2017. Similarly, data collected in 2019 will be analyzed and reported upon in 2020. Upon completion of a repeat map of a reach, the maps (DEMs) will be compared to compute the net change in the volume of sediment within the reach. These computations will distinguish between fine, coarse, and mixed sediment using recently developed acoustic sediment classification algorithms (Buscombe and others, 2014a, b), between sediment stored in the channel and eddies, and between sediment at high- and low-elevation. The resulting maps of bed sediment substrates are as highly resolved as the bathymetric maps, and therefore can be used within physical habitat classification efforts in other projects. These applications include the relative proportions of sand and gravel that are relevant to fish habitat and as substrate for aquatic invertebrates and the extent of submerged aquatic vegetation. In order to assess the temporal variability of bed sediment at selected sites, since 2012 there is an ongoing collection of annual time-series of bed sediment maps at sediment gaging sites, opportunistically during existing survey trips using multibeam and sidescan sonar. We propose to continue this sampling at these specific sites. These insights will be used to assess the scope of physical habitat suitability modeling within other projects.

Two components of this project element (estimating total sand storage by measurements of sand thickness and measuring bedload sand transport) were cut to accommodate required budget reductions. These components are described in Section 8, below.

Outcomes and Products

- Report and maps for RM 166 to 225 (mapped in 2017).
- Report/journal article on geomorphic changes in upper Marble Canyon, 2013-2016.
- Report/journal article on geomorphic changes in lower Marble Canyon and eastern Grand Canyon describing effects of HFE Protocol on sandbars and sand storage, 2009-2019.

Project Element B.3. Control network and survey support

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Project Description

The purpose of this project element is to provide a framework to enable high-accuracy change detection and to ensure that geospatial data collected in support of Project B and other projects are accurately referenced, precisely defined, and can be reliably compared with past and future datasets within Geographical Information Systems (GIS). Informed decision-making requires knowledge of the accuracy associated with geospatial data sets produced from many sources. The accuracies of each are determined by comparison with independent sources of higher accuracy referencing a common datum (or geospatial reference system). An accurate control network provides access to the common datum for change detection, the means to validate the accuracy of subsequent data products, and ensures that spatially referenced observations are repeatable. The sandbar and sediment storage project-elements collectively rely on the accurate positions of hundreds of monuments to validate equipment calibrations and provide continuity between disparate methods. For example, the merging of LiDAR (light detection and ranging remote sensing), sonar, digital imagery and total station measurements along a reach of river requires consistent reference, even though each are measured from different locations. This project element ensures that these and other data products can be precisely aligned. As such, the ability to provide accurate positions and determine product accuracy benefits several projects including the Streamflow, Water Quality, and Sediment Transport and Budgeting (Project A), Riparian Vegetation (Project C), Geomorphic Effects of Dam Operations (Project D), Geospatial Science and Technology (Project K), and Remote Sensing Overflight (Project L) projects.

The control network is a set of monumented and documented reference marks at more than 1200 locations along the river corridor and on the rim together with the collection of observations that determine the relative and absolute positions of those points. These stations serve as the basis for referencing all ground- and air-based monitoring observations. Uncertainties in these positions are particularly critical for the sediment storage project, because small inaccuracies (e.g. centimeters) can lead to very large uncertainties in measured volumetric changes sand storage when calculated over long reaches. For example, a vertical error of 5 cm distributed over a 30-mile sediment monitoring reach is approximately equivalent to a 250,000 m^3 of sand (about 162,500 metric tons). This amount of sand can often be the difference between being able or unable to determine the sign of a sediment budget. Current network accuracy is ~5 cm at 95% confidence, and periodic re-occupations are required to maintain or improve network accuracy. Thus, one of the primary ways in which we can reduce uncertainty in estimates of sand storage change is to increase the accuracy of network positions through repeat observations and to add control where coverage is limited.

At present, 77% of the river corridor from GCD to Diamond Creek has a sufficient number of control points to support monitoring activities. The remaining 23% (about 80 km), between Bright Angel Creek (RM 88) and National Canyon (RM 166), will be addressed in this work plan and network adjustment results will be made available prior to the next aerial overflight and channel mapping data collection efforts. Global Navigation Satellite System (GNSS) data will be collected at stations along the rim, while simultaneously observing stations along the river corridor, thereby establishing accurate control points along the river corridor that are linked to satellite observations and constrained to a geospatial datum. GNSS-derived control points will be connected via conventional total station measurements in locations where GNSS observations are not practical (because of steep canyon walls), thereby establishing a network of survey control that will provide near continuous coverage for all proposed elements in Project B. Additional, but more limited, survey control work will occur as necessary downstream from Diamond Creek in support of element B.6 (unfunded).

Storage, archiving, and documentation of the control network database

Coordinates, datum descriptions, and accuracy results are provided in a format compatible with Federal Geographic Data Committee (FGDC) delivery standards. The FGDC requires network (absolute) and local (relative) accuracy be reported for federally funded spatial data products. GNSS base stations are published (blue-booked) within the National Geodetic Survey Integrated Database (NGSIDB). The control network data are stored in a GIS database that is linked to gcmrc.gov. The survey staff works with GIS staff to maintain and update the database as needed.

Outcomes and Products

- Control network adjustment for lower Marble Canyon and eastern Grand Canyon (contributes to product in Project Element B.2).
- Report/ article on combining GNSS observations and historical leveling data for more accurate elevations and datum adjustments that account for modern satellite data.
- Collect, process, adjust and publish geodetic control data for the remaining areas of the CRe, including Bright Angel Creek to National Canyon. Results will be used as constraints for aerial imagery and channel mapping efforts of 2020.
- Updates to the NGSIDB of all available Height Modernization and benchmark stations used for GNSS overflight reference.
- Updated database with results of the entire CRe geodetic control network.

6. References

Alvarez, L.V., Schmeeckle, M.W., and Grams, P.E., 2017, A detached eddy simulation model for the study of lateral separation zones along a large canyon-bound river: Journal of Geophysical Research—Earth Surface, v. 122, no. 1, p. 25-49, http://dx.doi.org/10.1002/2016JF003895.

Andrews, E.D., and Vincent, K.R., 2007, Sand deposition in shoreline eddies along five Wild and Scenic Rivers, Idaho: River Research and Applications, v. 23, no. 1, p. 7-20, http://dx.doi.org/10.1002/rra.960.

Ashley, T., McElroy, B., Buscombe, D., Grams, P.E., and Kaplinski, M., 2016, Estimating bedload from gage data to improve flux-based sediment budgets—presentation, *in* Geological Society of America (GSA) annual meeting, Denver, Colo., September 28, 2016, http://dx.doi.org/10.1130/abs/2016AM-287370.

Bogle, R., Velasco, M., and Vogel, J., 2012, An automated digital imaging system for environmental monitoring applications: U.S. Geological Survey Open-File Report 2012-1271, 18 p., https://pubs.er.usgs.gov/publication/ofr20121271.

Buscombe, D., 2013. Transferable wavelet method for grain-size distribution from images of sediment surfaces and thin sections, and other natural granular patterns: Sedimentology, v. 60, no. 7, p. 1709–1732, http://dx.doi.org/10.1111/sed.12049.

Buscombe, D., 2017, Shallow water benthic imaging and substrate characterization using recreational-grade sidescan-sonar: Environmental Modelling & Software, v. 89, p. 1-18, http://dx.doi.org/10.1016/j.envsoft.2016.12.003.

Buscombe, D., Grams, P.E., and Kaplinski, M.A., 2014, Characterizing riverbed sediment using high-frequency acoustics—1. Spectral properties of scattering: Journal of Geophysical Research—Earth Surface, v. 119, no. 12, p. 2674-2691, http://dx.doi.org/10.1002/2014JF003189.

Buscombe, D., Grams, P.E., and Kaplinski, M.A., 2015, Characterizing riverbed sediment using high-frequency acoustics—2. Scattering signatures of Colorado River bed sediment in Marble and Grand Canyons: Journal of Geophysical Research—Earth Surface, v. 119, no. 12, p. 2692-2710, http://dx.doi.org/10.1002/2014JF003191.

Buscombe, D., Grams, P.E., and Smith, S.M.C., 2015, Automated riverbed sediment classification using low-cost sidescan sonar: Journal of Hydraulic Engineering, v. 142, no. 2, available at http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0001079.

Chapman, K., Parnell, R., Smith, M.E., Grams, P.E., and Mueller, E.R., 2016, Evaluating the effectiveness and long-term sustainability of experimental floods on the Colorado River in the Marble Canyon reach of Grand Canyon, AZ—presentation, *in* Geological Society of America (GSA) annual meeting, Denver, Colo., September 26, 2016, http://dx.doi/org/10.1130/abs/2016AM-280556.

Grams, P.E., Buscombe, D., Topping, D.J., Hazel, J.E., Jr., and Kaplinski, M.A., 2015, Use of flux and morphologic sediment budgets for sandbar monitoring on the Colorado River in Marble Canyon, Arizona, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 1144-1155, http://acwi.gov/sos/pubs/3rdJFIC/Proceedings.pdf.

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., Schmidt, J.C., and Topping, D.J., 2007, The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000: Geological Society of America Bulletin, v. 119, no. 5-6, p. 556-575, http://dx.doi.org/10.1130/B25969.1.

Grams, P.E., Topping, D.J., Schmidt, J.C., Hazel, J.E., Jr., and Kaplinski, M.A., 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, no. 2, p. 361-381, http://dx.doi.org/10.1002/jgrf.20050.

Griffiths, R.E., and Topping, D.J., 2015, Inaccuracies in sediment budgets arising from estimations of tributary sediment inputs—An example from a monitoring network on the southern Colorado Plateau, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 583-594, https://acwi.gov/sos/pubs/3rdJFIC/Contents/4A-Griffiths.pdf.

Hazel, J.E., Jr., Grams, P.E., Schmidt, J.C., and Kaplinski, M., 2010, Sandbar response in Marble and Grand Canyons, Arizona, following the 2008 high-flow experiment on the Colorado River: U.S. Geological Survey Scientific Investigations Report 2010-5015, 52 p., http://pubs.usgs.gov/sir/2010/5015/.

Hazel, J.E., Jr., Kaplinski, M., Parnell, R.A., Kohl, K., and Schmidt, J.C., 2008, Monitoring fine-grained sediment in the Colorado River ecosystem, Arizona—Control network and conventional survey techniques: U.S. Geological Survey Open-File Report 2008-1276, 15 p., http://pubs.usgs.gov/of/2008/1276/.

Hazel, J.E., Jr., Topping, D.J., Schmidt, J.C., and Kaplinski, M., 2006, Influence of a dam on fine-sediment storage in a canyon river: Journal of Geophysical Research—Earth Surface, v. 111, no. F1, p. 1-16, http://dx.doi.org/10.1029/2004JF000193.

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., Kohl, K., Buscombe, D., and Tusso, R.B., 2017, Channel mapping river miles 29–62 of the Colorado River in Grand Canyon National Park, Arizona, May 2009: U.S. Geological Survey Open-File Report 2017-1030, 35 p., https://doi.org/10.3133/ofr20171030.

Kaplinski, M., Hazel, J.E., Jr., Parnell, R., Breedlove, M.J., Kohl, K., and Gonzales, M.F., 2009, Monitoring fine-sediment volume in the Colorado River ecosystem, Arizona—Bathymetric survey techniques: U.S. Geological Survey Open-File Report 2009-1207, 33 p., http://pubs.usgs.gov/of/2009/1207/of2009-1207.pdf.

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., and 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.

Magirl, C.S., Webb, R.H., and Griffiths, P.G., 2005, Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000: Water Resources Research, v. 41, no. W05021, p. 1-10, http://dx.doi.org/10.1029/2003WR002519.

Mueller, E.R., Grams, P.E., Schmidt, J.C., Hazel, J.E., Jr., Alexander, J.S., and Kaplinski, M., 2014, The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River Basin: Geomorphology, v. 226, p. 65-75, http://dx.doi.org/10.1016/j.geomorph.2014.07.029.

Mueller, E.R., Grams, P.E., Hazel, J.E., Jr., and Schmidt, J.C., 2016, Variability of eddy sandbar response during two decades of controlled flooding along the Colorado River in Grand Canyon—presentation, *in* Geological Society of America (GSA) annual meeting, Denver, Colo., September 28, 2016, http://dx.doi.org/10.1130/abs/2016AM-284233.

Pemberton, E.L., 1976, Channel changes in the Colorado River below Glen Canyon Dam, *in* Third Federal Inter-Agency Sedimentation Conference, Denver, Colo., March 22-25, 1976, Proceedings: Sedimentation Committee, Water Resources Council, p. 5-61 to 5-73, http://www.gcmrc.gov/library/reports/physical/hydrology/Pemberton.pdf.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, http://dx.doi.org/10.1002/2015JG002991.

Schmidt, J.C., Topping, D.J., Grams, P.E., and Hazel, J.E., Jr., 2004, System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona—final report: Logan, Utah, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, cooperative agreement no. 1425-98-FC-40-22640, 107 p., http://www.gcmrc.gov/library/reports/Physical/Fine_Sed/Schmidt2004.pdf.

Schmidt, J.C., and Grams, P.E., 2011, The high flows—Physical science results, *in* Melis, T.S., ed., Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, p. 53-91, http://pubs.usgs.gov/circ/1366/.

Simon, A., and Rinaldi, M., 2006, Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response: Geomorphology, v. 79, no. 3-4, p. 361-383, http://dx.doi.org/10.1016/j.geomorph.2006.06.037.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport—1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515-542, http://dx.doi.org/10.1029/1999WR900285.

Twichell, D.C., Cross, V.A., and Belew, S.D., 2004, Mapping the floor of Lake Mead (Nevada and Arizona)—Preliminary discussion and GIS data release: U.S. Geological Survey Open-File Report 03-320, https://pubs.usgs.gov/of/2003/of03-320/.

Twichell, D.C., Cross, V.A., Rudin, M.J., and Parolski, K.F., 1999, Surficial geology and distribution of post-impoundment sediment of the western part of Lake Mead based on a sidescan sonar and high-resolution seismic-reflection survey: U.S. Geological Survey Open-File Report 99-581, 27 p., https://pubs.er.usgs.gov/publication/ofr99581.

U.S. Department of Interior, 2016, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

Wiele, S.M., Andrews, E.D., and Griffin, E.R., 1999, The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 131–145.

W Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p., http://pubs.er.usgs.gov/usgspubs/pp/pp1286.

Wright, S.A., and Kennedy, T.A., 2011, Science-based strategies for future high-flow experiments at Glen Canyon Dam, *in* Melis, T.S., ed., Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, p. 127-147, http://pubs.usgs.gov/circ/1366/.

Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., 2010, An approach for modeling sediment budgets in supply-limited rivers: Water Resources Research, v. 46, no. W10538, p. 1-18, http://dx.doi.org/10.1029/2009WR008600.

Wright, S.A., Schmidt, J.C., Melis, T.S., Topping, D.J., and Rubin, D.M., 2008, Is there enough sand? Evaluating the fate of Grand Canyon sandbars: GSA Today, v. 18, no. 8, p. 4-10, http://dx.doi.org/10.1130/GSATG12A.1.

Wright, S.A., Melis, T.S., Topping, D.J., and Rubin, D.M., 2005, Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, p. 17-31, http://pubs.usgs.gov/circ/1282/

7. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$173,274	$2,000	$4,500	$29,896	$200,308		$38,628	$448,606
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$201,283	$2,000	$15,000		$192,308		$39,728	$450,320
B.3	Control network and survey support	$63,755	$1,900	$15,000	$40,662			$18,873	$140,190
	Total B	**$438,312**	**$5,900**	**$34,500**	**$70,558**	**$392,616**	**$0**	**$97,228**	**$1,039,115**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$178,472	$2,000	$4,500	$32,388	$188,960		$62,182	$468,502
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$186,222	$2,000	$7,500	$91,006	$180,960		$79,978	$547,666
B.3	Control network and survey support	$58,304	$1,900	$15,000				$19,553	$94,757
	Total B	**$422,998**	**$5,900**	**$27,000**	**$123,394**	**$369,920**	**$0**	**$161,713**	**$1,110,925**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$183,826	$2,000	$4,500	$32,388	$200,308		$63,915	$486,938
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$213,542	$2,000	$7,500		$173,817		$63,205	$460,064
B.3	Control network and survey support	$60,053	$1,900	$15,000				$20,008	$96,961
	Total B	**$457,421**	**$5,900**	**$27,000**	**$32,388**	**$374,126**	**$0**	**$147,128**	**$1,043,962**

8. Experimental Project Budget (see Appendix 2e)

Proposed budgets for funding from the annual experimental fund or a contingency fund established to support research and monitoring of extended duration or proactive HFE experiments were they to occur in FY2018-20. Funds would cover costs associated with additional logistics, field personnel, and data processing. Reporting would be covered by existing projects. Some work will be conducted as part of planned annual monitoring trips. The costs for those trips is included in the project budget, not the HFE experimental budget. Thus, the budgets assume full (or nearly full) funding of all other Project B elements.

HFE Experimental Project. Sandbar response to differences in HFE magnitude and duration

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Matt Kaplinski, Research Associate, Northern Arizona University
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Project Description

The LTEMP EIS and ROD includes two experimental activities designed to improve sandbar and sediment resources (extended duration HFEs and proactive HFEs) and one experimental activity that may cause increased sandbar erosion (trout management flows). Additionally, sediment-triggered HFEs implemented following the protocol that is extended in the LTEMP ROD could occur at any magnitude between 31,500 ft^3/s and 45,000 ft^3/s. Thus, there is also need to evaluate and compare the relative effectiveness of low-magnitude HFEs (<34,000 ft^3/s) and high-magnitude HFEs (>40,000 ft^3/s).

The primary purpose of this project element is to collect and analyze field data on the effects of any of those flow experiments on sediment resources when these experimental dam operations occur. However, the timing of those experiments is condition dependent. Further, uncontrollable factors, such as antecedent sandbar condition and sand supply, inevitably present challenges to interpreting the results of large-scale field experiments. Consequently, this project element includes a laboratory experimental study designed to address the same questions that motivate the experimental dam operations outlined in the LTEMP. The budget for this project element is separate from the rest of the Project B elements, because we propose this work be funded from either the annual experimental fund or a contingency fund established to support research and monitoring in support of condition-dependent experiments. The field components would occur only when the experimental dam operations occur and evaluation of the effects of those flow-release experiments is required.

Data collection before and after any HFE or experiment should designed and executed such that the information gained will maximize learning to guide future dam operations and experiments.

In order to achieve this, it is recommended that a workshop be convened to discuss proposed research, design sampling strategies, and discuss potential outcomes. It is recommended that this workshop be conducted prior to any HFE or other experiment that may occur after the start of the FY2018-20 work plan; thus, the workshop should be convened before the end of FY2017. Additional workshops may be required on an annual basis to plan and outline data collection activities during each potential HFE or other experiment that could occur during that year.

Extended duration HFEs

As defined in the LTEMP ROD, extended duration HFEs are restricted to implementation in the fall sand accounting period and would be triggered according to the same criterion used for other sediment-triggered HFEs—that the sand mass balance for the fall sand accounting-period (July 1 – December 1) remain positive through HFE implementation based on model projections. The original HFE protocol allows for HFE duration of up to 96 hours with a peak magnitude of 45,000 ft^3/s. The extended duration HFEs may be 144, 192, or 250 hours in duration; however, the first test of an extended duration HFE is limited to 192 hours. Extending HFE duration is based on the hypothesis that, under conditions of enriched sand supply, longer duration HFEs will maintain elevated suspended sand concentrations for longer than the duration of a 96-hour HFE, resulting in more deposition and larger sandbars.

The key information needed to evaluate the effects of extended duration HFEs on sediment resources will be:

1) Measurements of suspended sand concentration during each entire HFE,
2) Measurements of sandbar size before and after the extended duration HFE, and
3) Daily observations of sandbar dynamics during the HFE.

The measurements of suspended sand concentration will be used to determine if sand concentrations remain elevated throughout the extended HFE or if sand supply becomes depleted and concentrations decline, and these measurements are included in the regular Project A monitoring. The basis for evaluating the effects of extended duration HFEs on sandbar deposition will be by comparison with measurements of deposition for other HFEs. Images from the remote cameras will be used for a qualitative comparison at all sites and a quantitative comparison at some sites (see project element B.1). However, pre- and post-HFE topographic surveys are required for a quantitative comparison with measurements made before and after the 1996, 2004, and 2008 HFEs. Because the extended duration HFEs are limited to the fall accounting period, data collected in the fall sandbar-monitoring trip, which occurs annually in early October, will be used as the pre-HFE sandbar measurement, which saves logistical costs. One additional sandbar-monitoring trip will be required following the extended duration HFE. The focus of the pre- and post-HFE study will be on deposition above the 8,000 ft^3/s stage. Therefore, the surveys will be for sandbar topography only and do not require bathymetry. Additional information will be gained by conducting daily surveys during the extended duration

HFE at two locations. These surveys will allow for comparison between observed sandbar deposition rates and main-channel suspended sand concentrations. Finally, we will compare observed changes in sandbar volume to predictions based on site-specific sandbar modeling (Element B. 3) to evaluate the predictive capability of the modeling approach.

Proactive HFEs

Proactive HFEs are defined in the LTEMP EIS and ROD as releases of up to 45,000 ft^3/s and up to 24-hour duration that would occur in spring (April – June) in advance of scheduled equalization flows. The intended purpose of proactive HFEs is to create sand deposits above the expected stage of equalization flows, such that those deposits would not be subject to erosion during the equalization flows. Evaluation of the effectiveness of the proactive HFEs, therefore, requires:

1) Measurements of sandbar deposition by proactive HFEs followed by
2) Measurements of erosion of the deposited sandbars through and immediately following the period of summer equalization flows.

This would require surveys of sandbar topography immediately following the proactive HFE and following the equalization flows. Images from remote cameras already in place would be used to monitor the portions of sandbars exposed above water during the equalization flows (see project element B.1). The post-equalization flow survey would be accomplished on the annual sandbar-monitoring trip in early October. The post-HFE survey would require one additional survey trip. If river discharge is less than about 16,000 ft^3/s during the survey, this could be accomplished with topography only. If discharge is higher, bathymetric measurements would be required to enable surveying the entire sandbar above the 8,000 ft^3/s stage. Surveying the sandbar down to the 8,000 ft^3/s stage is required for the purposes of comparison with other surveys.

Trout management flows

Trout management flows are described in the LTEMP EIS and ROD as repeated cycles of flow fluctuations between high flows of approximately 20,000 ft^3/s and low flows of 8,000 ft^3/s or lower. The high-flow component would last between two and seven days with the low-flow component lasting for less than 24 hours. These flows are expected to cause increased rates of sandbar erosion. The requirement for monitoring sandbar response would depend on the expected number of fluctuation cycles in a given trout management flow (TMF) event. If a TMF event consists of only a few cycles, the increased amount of erosion compared to normal fluctuations would likely be small and difficult to measure. Under this scenario, observations from existing remote cameras will be used to determine if sandbar erosion rates are affected by these flows, particularly at the sites where georectification allows for daily to weekly calculation of area and, potentially, bar volume change. In contrast, if a TMF event consists of many fluctuation cycles, the expected additional erosion might require additional sandbar surveys to quantify sandbar change at all sites.

Low-magnitude HFE

A low-magnitude HFE would occur according to the HFE protocol either when there is insufficient sand for a larger-magnitude HFE, or if there is insufficient capacity to release more than that amount of water with the combined capacity of the powerplant and the bypass tubes. We define a low-magnitude HFE as a release that is between the powerplant capacity of 31,500 ft^3/s and 34,000 ft^3/s. Because sandbar response to a low-magnitude HFE could be very different from the response to a high-magnitude HFEs, quantification of the magnitude of this difference would be useful for planning purposes. If the low-magnitude HFE occurred in the fall, monitoring the response would require one additional post-HFE sandbar survey trip, using the regular monitoring trip as the pre-HFE condition. If the low-magnitude HFE occurred in the spring, two additional sandbar survey trips would be required.

Outcomes and Products

- Update on results at Annual Reporting Meeting.
- Report or journal article describing field data and effects of extended/proactive HFEs, should they occur.

9. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element B.(i). Bathymetric and topographic mapping for monitoring long-term trends in sediment storage

Project Description

The parts of this project element that were reduced/eliminated to meet the budget cuts are described below.

- Proposed budget for components cut (including burden): \$91,000 (FY2018); \$97,000 (FY2019); \$120,000 (FY2020).

The purpose of this project component is to develop estimates of the total mass and volume of sand storage. Information on the volume of sand stored within the channel bed is valuable for three primary reasons. First, understanding the dynamics of sandbars in eddies requires information on the sand replenishment potential from the adjacent eddy and channel, which in turn necessitates information on the thickness of sand deposits in those areas. Second, only through estimating the total sand storage in the system can we evaluate the long-term importance of observed net changes in sand storage by repeat channel mapping and sediment flux monitoring (Project A). Third, the sediment routing model used to design HFEs requires information on the active layer sand thickness on the channel bed. Currently, in lieu of better information, this was set to 0.5 m, and the model was calibrated to this estimate (Wright and others, 2010). This simplification limits the predictive capacity of the model.

During the FY2015-17 work-plan, techniques for sub-surface imaging of the riverbed and estimation of sand thickness were developed and data were collected in upper Marble Canyon and west-central Grand Canyon with a frequency-modulated (CHIRP) echosounder system, which provides up to 10 m of subsurface penetration through sand (Fig. 6).

In this work plan, we propose to use the same sub-bottom profiler to collect similar data in lower Marble Canyon and eastern Grand Canyon. These data and the data previously collected will be interpreted to provide sand thickness estimates for all areas mapped. Sediment classification maps (Buscombe and others, 2014a, b), rectified echograms from sidescan sonar (Buscombe and others, 2015; Buscombe, 2017), and bed sediment images from the eyeball system (Buscombe, 2013) will be used to aid interpretation of the CHIRP data. To provide estimates of sand thickness in areas of the bed not mapped with the CHIRP sonar, we will develop relationships between sand thickness and a suite of variables derived from the more spatially extensive channel mapping data products (principally, bathymetry, surface sediment maps) as well as channel geometry, geological and hydraulic characteristics. For Marble Canyon, we will compare maps of sand thickness and sediment texture to the output of the two-dimensional hydraulic model developed in Project Element B.5 (unfunded). We expect correlations between sand thickness and flow velocity. Other important explanatory variables are likely to be surface sand-grain-size, proximity to a debris fan (coarse sediment input), and pool depth-width scaling.

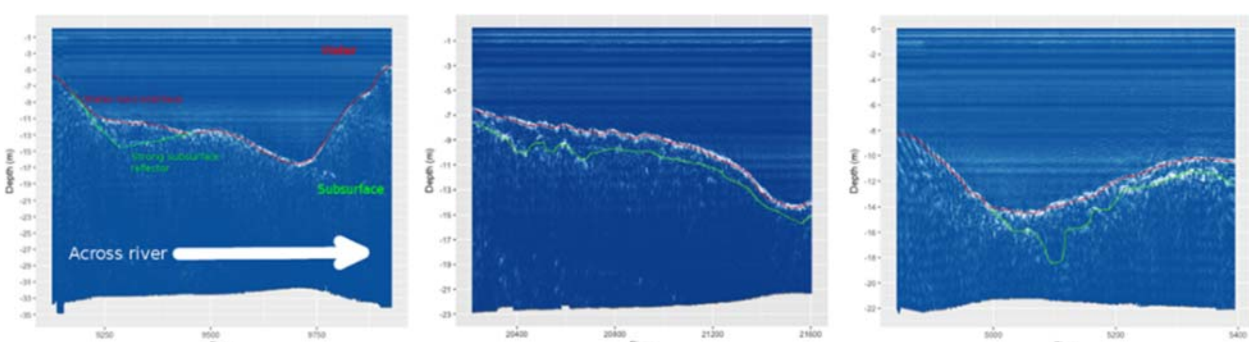

Figure 6. Example cross-sections from CHIRP sonar surveys. Red line is sediment-water interface. Green line is interpreted as the lower boundary of sand deposit. Sand thickness varies 0 - 5 m in these examples. The presence or absence of sand in areas with no strong subsurface reflector (green line) will be determined by analysis of multibeam-derived surface sediment maps.

By the end of FY2020, this project element will produce estimates, with uncertainties, of total in-channel sand storage along 146 miles of river (RM 0 - 30, RM 30 - 87, and RM 166 - 225), which comprises 65% of the monitored channel between Lees Ferry and Diamond Creek. These data will be a crucial component of ongoing studies into developing mechanistic explanations for sandbar dynamics during HFEs and during flows associated with ordinary dam operations.

During the FY2015-17 work plan, we collected several sets of high-quality measurements of migrating submerged dune fields at the Colorado River stream gage above Diamond Creek. We used these data to develop a probabilistic model that relates bedload flux to discharge, suspended sand flux and grain size (Ashley and others, 2016) for the purpose of reducing uncertainty in the measurements of sand flux made in Project A. Under Project B for FY2018-20, we propose to apply that model to additional gaging sites. The model is in a Bayesian framework that is designed to be updated (by recomputing posterior probabilities of model parameters) when new data become available. Data necessary to extend the model will be collected at the gaging stations at RM 30, RM 61, and RM 87 during the 2019 channel mapping campaign. Data will also be collected on Project A gage-station maintenance trips to avoid added logistics costs.

This project element will result in extending the existing model to predict instantaneous bedload flux from measured discharge and suspended sediment flux and grain size, calibrated to each of the five gaging stations between RM 30 and RM 225. Model outputs will be incorporated into the existing sediment monitoring pages on www.gcmrc.gov, for quasi real-time bedload estimates. These improved total load (bedload plus suspended load) estimates will allow for more accurate tracking of changes in sediment storage and for designing HFEs.

Outcomes and Products

- Estimates, with uncertainties, of total in-channel sand storage along 146 miles of river (RM 0 - 30, RM 30 - 87, and RM 166 - 225), which comprises 65% of the monitored channel between Lees Ferry and Diamond Creek.
- Report/journal article on development of CHIRP sonar-derived sand thickness measurements, and estimates of total sand storage.
- A generalized model that predicts instantaneous bedload flux from measured discharge and suspended sediment flux and grain size, calibrated to each of the five gage sites between RM 30 and RM 224
- Report/journal article on bedload measurements, model development, and application to several gaging station sites for estimates of total load transport.

Project Element B.(ii). Characterization and predictive modeling of sandbar response at local and reach scales

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Daniel Buscombe, Research Professor, Northern Arizona University
Alan Kasprak, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Project Description

- Proposed budget for Objectives 1 and 2, Numerical Modeling (including burden): \$86,500 (FY2018); \$117,300 (FY2019); \$78,900 (FY2020).
- Proposed budget for Objective 3, Physical Modeling (including burden): \$151,700 (FY2018); \$115,200 (FY2019); \$122,300 (FY2020).

A primary goal of the LTEMP is to increase the size and abundance of sand bars. While annual surveys and remote cameras provide an assessment of changes in bar size, linking physical or numerical models to observed bar response is necessary to provide a framework for evaluating the effects of different flow scenarios. In the FY2015-17 work plan, progress was made on identifying groupings (classes) of sandbars based on geomorphic setting that respond similarly to HFEs and other dam releases, and on developing a simple site-based numerical model (hereafter, morphodynamic model) for predicting sandbar volume changes based on site geometry, measured or synthetic streamflow and sand concentration data, and physically-based sand deposition and erosion equations. Application of the morphodynamic model requires information on the rates of water (and, therefore, sediment) exchange between the channel and eddy (eddy exchange rate), which can be quantified using 2-dimensional hydraulic modeling. Thus, we propose three linked modeling elements during FY2018-20 to improve capabilities for predicting sandbar response to dam operations, including HFEs:

1) Develop two-dimensional, reach-scale hydraulic models for Marble Canyon where extensive channel mapping data are available;

2) Continue development and validation of the morphodynamic model to predict bar response to HFEs and normal dam operations for different bar groupings using modeled eddy exchange rates; and

3) Use laboratory experiments (physical modeling) to explicitly link characteristics of HFE shape to sandbar morphology that is virtually impossible in a field or numerical setting.

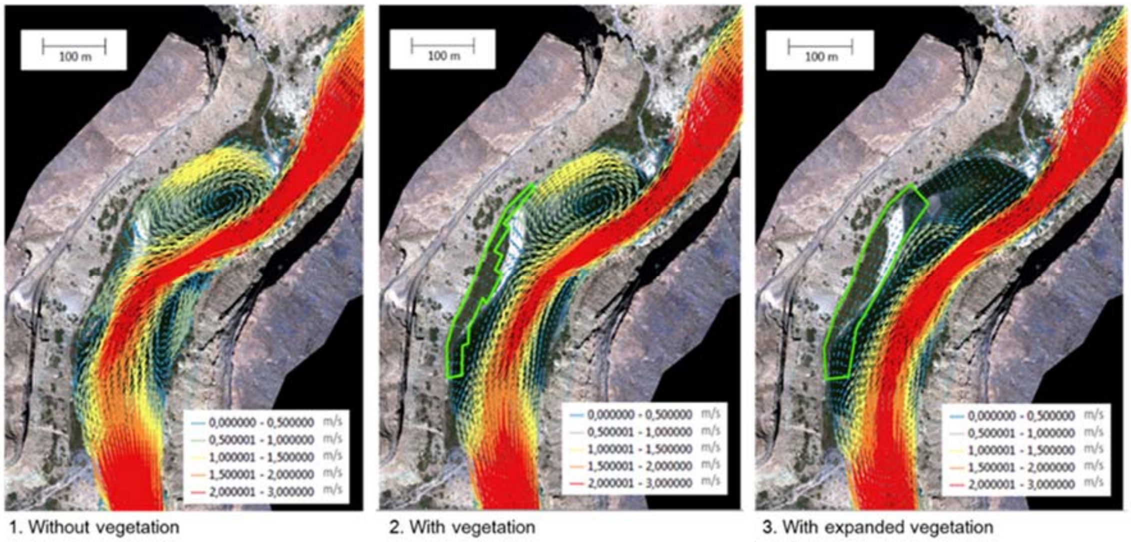

Figure 7. Changes in flow hydraulics during a flood at the Buckfarm (RM 41) sandbar modeled using Delft3d. 1) Without vegetation; 2) with the observed vegetation; and 3) with expanded vegetation (outlined in green).

Objectives 1 and 2: Numerical modeling of streamflow and sandbar response to HFEs

Two-dimensional hydraulic modeling in Marble Canyon will allow us to quantitatively address a primary management question at large spatial scales: Are differences in sandbar response to HFEs and other dam operations driven by local flow hydraulics, or more strongly linked to flow and sediment supply boundary conditions, and how does that vary among eddies?

In FY2015-17 we classified sandbar types based on geomorphic setting using a Principal Components Analysis (PCA) and demonstrated that there are predictable differences in bar response to HFEs and site-scale sediment storage as a function of discharge within the PC-space (Mueller and others, 2016). The hydraulic modeling will allow us to directly link these differences to the flow hydraulics that control bar sedimentation. We hypothesize that eddies with higher velocities and stronger flow recirculation patterns typical of more narrow reaches tend to be more dynamic and thus potentially more responsive to different flow scenarios and HFE frequency. In lower velocity settings, vegetation encroachment stabilizes sandbar deposits and long-term increases in bar volume reflect the cumulative flow history that may successively increase vegetated bar elevation. This project element will be collaborative with Project C to better understand the feedbacks between vegetation encroachment and sandbar dynamics (Fig. 7), and how that influences the riparian species guilds associated with different hydraulic environments and inundation frequencies. We will use bathymetry and near-channel topographic data collected during previous channel mapping trips in Marble Canyon between 2009 and 2016, along with upland topographic data collected in the 2013 aerial overflight, to produce two-dimensional (i.e., depth-averaged) hydraulic models using freely available software packages such as Delft3d (Figure 7) or iRIC (i-ric.org) . These numerical models predict flow depth, velocity, and inundation extent (modeled or "virtual" shorelines) from low flows (i.e., < 8,000 ft3/s) up to the historic flood of record (210,000 ft3/s). Combined with a recently-developed two-dimensional numerical flow model for Glen Canyon, this work will enable near-continuous predictions of inundation extents and river channel hydraulics important to riparian vegetation diversity (Project C), aeolian transport of sand (Project D), aquatic ecology (Project F), and fish habitat variability (Projects G, H, and I) throughout Glen Canyon and Marble Canyon.

Because hydraulic modeling alone does not simulate sandbar deposition and erosion, evaluating bar response requires a modeling element that couples eddy hydraulics and measured suspended sediment concentration, discharge, and grain size (Project A) to predict sandbar area and volume change. Thus, a primary objective of this research is to use the two-dimensional streamflow model to better parameterize the physically-based morphodynamic model of individual bar response that uses the 15-minute record of flow, stage, sediment concentration, and sediment grain size from any of the gaging stations in the canyon to predict changes in sandbar size for individual bars or groupings of similar bars (Figure 8). This model directly links the continuous sediment and flow monitoring of Project A with sandbar monitoring as part of Project B using a physically-based approach modified from Andrews and Vincent (2007). Model predictions can be validated using the sandbar area and volume data sets (Fig. 8) but these validation data sets are at much coarser resolution than the 15-minute model predictions and do not capture the changes in sandbar form that occur between surveys. As a result, we will use results from the remote camera study (Project Element B.1) to link daily or weekly changes in bar area to the sub-daily predictions of the model. Quantifying changes in bar area from the remote cameras will allow us to define erosion rates for different sites on daily to weekly timescales, thereby addressing one of the great uncertainties in understanding long-term bar behavior, especially between controlled floods. The hydraulic model will enable us to link local hydraulics to the episodic versus gradual erosion processes that dominate following HFEs, and quantify site-specific differences in eddy velocity ("eddy exchange rates"). By using modeled eddy exchange rates (from the 2-d hydraulic model) and observed erosion rates (from remote cameras), the model will effectively have no free parameters and be a significant advancement over previous modeling attempts that have often involved empirical parameterizations that are not directly related to the processes of sandbar deposition and erosion (i.e. models based directly on flow discharge). Combined with the PCA analysis of sandbar groups (Mueller and others, 2016), we can develop predictions of potential short-term or long-term bar response for sites with differing degrees of bar dynamism and vegetation encroachment under natural or synthetic flow scenarios.

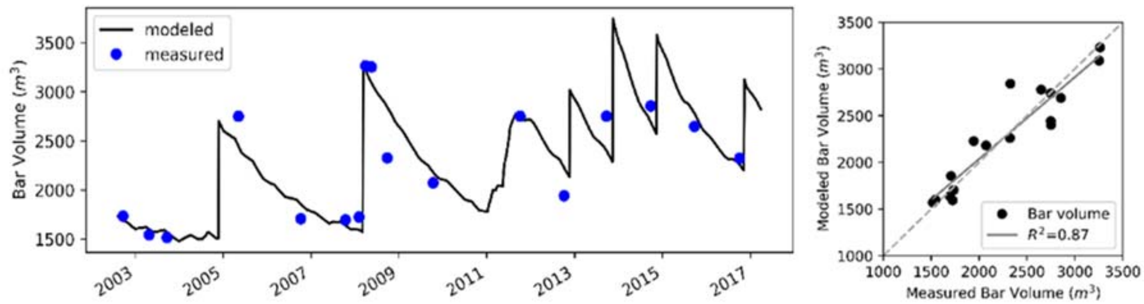

Figure 8. Modeled sandbar volume for the Group-1 bars of Mueller and others (2016), a composite of nine geomorphically similar bars, based on the flow and sediment gaging record at the 30-mile gage 2002 to present.

Objective 3: Physical modeling of bar response to HFE hydrograph scenarios

One of the challenges faced in implementation of the HFE protocol is a lack of information for predicting sandbar response to HFEs of different magnitude, duration, or hydrograph shape. Because the HFE variations that would occur in the context of the LTEMP are condition dependent, it is not clear when or if those tests will occur. Moreover, the LTEMP does not include experiments to evaluate if/how variation in HFE magnitude or hydrograph shape (ramp rates) may affect sandbar responses to HFEs. Furthermore, lack of controlled conditions in the field coupled with the expense of collecting detailed field measurements around each HFE makes it difficult to address questions about the effect of hydrograph characteristics on sandbar response based on field data alone. In fact, some questions might be almost impossible to address without the ability to control discharge and sediment supply systematically across a range of values as in a laboratory setting.

The purpose of the physical modeling part of this project element is to investigate the effects of hydrograph shape on sandbar deposition and erosion with a set of laboratory flume experiments. Laboratory experimentation will allow us to explore HFE hydrograph design options in terms of peak flow (below, at, or above power plant capacity), hydrograph asymmetry (up- and down-ramp rates), and duration, in order to evaluate how these variables affect sandbar deposition and erosion. The results will allow us, for example, to assess what combination of these three would maximize the volume and minimize the slope of subaerial (immediately post-flood) sandbars. The proposed work will investigate the immediate post-flood sandbar volume and slope under a very large range of experimental flows that will mimic various HFE hydrograph scenarios.

A short pilot study was conducted in 2016 at St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN. This pilot study demonstrated that it is possible to design a flow constriction to create an eddy sandbar, and that flows could be adjusted to manipulate the bar. Laboratory conditions were designed using a 3-D hydraulic model (Alvarez and others, 2017). We propose to build on the success of these pilot experiments with a full experimental program to study, in isolation, the effects of flow magnitude, duration and asymmetry (upramp and downramp rates) on sandbars, in order to test the following hypotheses:

1) Flow duration is the biggest lever on total sandbar deposition;
2) Flow magnitude is the biggest lever on sandbar elevation; and
3) Slower down-ramp rates during the recession limb of an HFE result in gentler sandbar slopes.

To conduct these experiments, a debris fan and eddy complex will be created within the flume and the channel bed will be filled with sand. First, a series of experiments will establish the time scales required for bars to reach equilibrium under different flow magnitudes (low, medium and high). This will be necessary to establish the length of the “long duration” flows, and to scale the medium and short duration flows accordingly. Then, another series of experiments will be conducted whereby three flow variables are independently varied, namely duration ('pulse' and 'surge'), magnitude ('large' and 'small') and hydrograph symmetry ('symmetric', 'flood-dominated', 'ebb-dominated'). During the experiments, sand will be fed in above the constriction at a constant rate. During each experiment, detailed measurements of the evolution of the sandbar will be made, to assess the effect of each flow treatment on overall sandbar slope and volume, sandbar elevation, and slopes and volumes above different flow levels.

Outcomes and Products

- A two-dimensional hydraulic model, with spatially explicit results, including mapped depth, velocity, and inundation extent (shorelines) for different flow magnitudes.
- Report or journal article on variability of flow hydraulics at the site and reach scale, and linkages to riparian vegetation, using results from the two-dimensional hydraulic model.
- Report or journal article on the morphodynamic model, including original python source code, that couples the streamflow and sediment transport measurements of Project A with the survey and remote camera sandbar monitoring data of Project B.1.
- Report or journal article describing laboratory experimental methods and results, with a synthesis of relative importance of flow duration, magnitude and hydrograph shape on sandbar volume and slope.

Project Element B.(iii). Research Study: Bank erosion, bed sedimentation, and channel change in the Colorado River arm of the Lake Mead Delta in Grand Canyon

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Daniel Buscombe, Research Professor, Northern Arizona University
Ed Schenk, Physical Scientist, Grand Canyon National Park
John C. Schmidt, Professor, Utah State University

Project Description

- Proposed budget (including burden): \$71,700 (FY2018); \$75,100 (FY2019); \$75,800 (FY2020).

Erosion of sediment from high banks and subsequent remobilization in the Colorado River arm of the Lake Mead Delta presents significant navigation and habitat management issues in the western part of Grand Canyon. All large reservoirs trap incoming sediment, and post-dam sedimentation in Lake Mead has been periodically studied since the completion of Hoover Dam in 1935 (Twitchell and others, 1999, 2004). Current and projected decline in water supply and total allocation of Colorado River water would suggest that Lake Mead and Lake Powell are likely to stay well below full pool for the foreseeable future, converting the upstream parts of these reservoirs to riverine reaches that are rapidly evolving and redistributing sediment from the upper to lower parts of the delta. Thus, river-reservoir system management must consider the physical and geochemical effects of erosion and redistribution of this legacy sediment.

Currently, little is known about how the rate and magnitude of vertical incision and lateral erosion of Lake Mead Delta deposits by the Colorado River is affecting long-term channel stability and morphological evolution. The primary objectives of this research are to:

1) Quantify the rates and spatial patterns of vertical incision and lateral bank erosion of former reservoir sediment in the now riverine reach of the Lake Mead Delta; and
2) Link transient river channel change and bed sedimentation to increased sediment supply from banks and lateral channel migration.

We hypothesize that bank erosion rates have increased in recent years as a result of reservoir drawdown and bed incision, and that following initial channel incision, rapid bluff erosion causes bed sedimentation and channel widening which may promote further bank erosion. As bank erosion progresses and the incised river channel widens, we may expect a decrease in sediment supply and a stabilization of the channel planform inset within the delta deposits. In this case, we may hypothesize that vegetation will eventually stabilize bars and form a floodplain inset within the high banks composed of Lake Mead Delta sediments. Whether, and how often, this cycle repeats itself depends on the downstream base level control and the frequency of incision events associated with changes in reservoir level and knickpoint migration. This sequence of incision, widening, and stabilization has been described for a number of degrading river systems (Simon and Rinaldi, 2006).

The upstream end of Lake Mead that is within Grand Canyon National Park is the final reach for many Grand Canyon river trips, is the centerpiece of river running operations by the Hualapai tribe, and is inherently within the purview of the GCDAMP, being a reach of the Grand Canyon and one that now affords a river-running experience. This section of the Colorado River in Grand

Canyon is perhaps the busiest section of the river, in terms of boat traffic, in the National Park. It is increasingly difficult for the Hualapai tribe to maintain docks for their upstream fleet, and bed sedimentation often causes boat beaching and difficulty accessing the Pearce Ferry boat ramp. The delta deposits also inhibit natural campground development because there are few beaches adjacent to the steep banks. Furthermore, Lake Mead has a self-sustaining population of endangered razorback sucker (*Xyrauchen texanus*) that must use this reach of river to migrate between the reservoir and riverine environments. Thus, erosion of reservoir sediment and subsequent remobilization in the Colorado River arm of the Lake Mead Delta presents significant navigation issues, but also provides a dynamic riverine environment that may provide beneficial habitat to some native fish in the western part of Grand Canyon.

The sediments of the Lake Mead Delta extend upstream to approximately the location of Separation Rapid in Grand Canyon, about 40 river miles upstream from Pearce Ferry. Since 2000, Lake Mead water levels have declined approximately 40 meters. The Colorado River has subsequently incised through newly exposed delta sediments, persistently eroding tall banks of fine-grained lake and delta deposits (Fig. 9). Erosion of these banks delivers sediment to the river resulting in ever-shifting sandbars throughout much of the lower river corridor between Separation Rapid and Pearce Ferry. Downstream from Pearce Ferry, the Colorado River flows over a ledge of poorly consolidated bedrock (Pearce Ferry rapids) because the path of the incised channel does not follow its pre-reservoir course. This ledge (knickpoint) creates a significant navigation hazard and may also affect native fish migration from the reservoir upstream to the Colorado River in Grand Canyon. Additionally, this bedrock ledge provides the downstream base-level for the incising section of the lower Colorado River in Grand Canyon National Park, and thus plays an important role in regulating incision and sediment evacuation from upstream reaches.

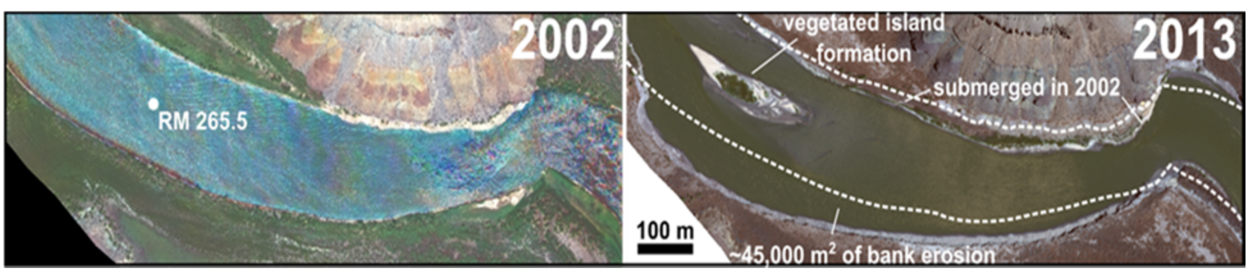

Figure 9. Example of bank erosion and mid-channel bar formation between 2002 and 2013 for an approximately 1 km long reach between RM 265 and 266. Dashed white line shows 2002 shoreline.

In order to address the primary research questions above, we intend to study channel response to reservoir drawdown along the Colorado River arm of the Lake Mead Delta in collaboration with the National Park Service (NPS). Preliminary surveys of bank topography were collected in collaboration with Ed Schenk of the NPS during the 2016 HFE. In addition, we will work with the Hualapai tribe to develop a plan to study issues associated with river bed sedimentation and bank erosion in reaches critical for boat navigation. In the first part of our analysis, we propose to use available remote sensing data sets and repeat topographic surveys to document historical changes in bank and river channel morphology. The second part of our analysis will include short field data collection trips, in conjunction with LiDAR surveys of banks, to map changes in the channel morphology. The shifting sandbars of the Colorado River where it flows through Lake Mead Delta sediments presents a considerable navigational hazard. This is an extremely challenging environment for bathymetric mapping because of very shallow and highly turbid water, which precludes many sonar and image-based methods. We will use a very low draft, wide-angle, dual- LiDAR- sonar system specially designed for swath mapping in shallow water, collecting swath data up to 10 times the water depth and LiDAR topography of sediment banks up to 100 m away. We will work with the Hualapai Tribe and NPS to create a baseline map of the channel thalweg and other navigable parts of the channel and, if possible, document thalweg migration rates. We will also explore other remote sensing technologies that may allow for more continuous documentation of thalweg and sandbar migration patterns. Because similar issues exist upstream along the deltas of the Colorado and San Juan arms of Lake Powell, this research project also could provide guidance for management of other large reservoirs in the Colorado River Basin.

Outcomes and Products

- Report/journal article on bank erosion, bed sedimentation, and channel change of the Colorado River area of the Lake Mead Delta.

Project C. Riparian Vegetation Monitoring and Research

1. Investigators

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Brad Butterfield, Research Assistant Professor, Northern Arizona University
Emily Palmquist, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Durning, Research Specialist Sr., Northern Arizona University

2. Project Summary

This project seeks to monitor riparian vegetation response to dam operations in order to determine if the LTEMP Resource Goals for riparian vegetation are being met (Elements 1 and 2), use the data created by riparian vegetation monitoring in Elements 1 and 2 to address gaps related to predicting the responses of vegetation to dam operations (Element 3), and support the implementation of experimental vegetation treatments directed by the LTEMP ROD (Element 4).

Monitoring the state of riparian vegetation along the mainstem is ongoing and critical for understanding the effects of dam operations on riparian vegetation and associated resources. Long-term monitoring assesses if riparian vegetation is being maintained "in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate" and assesses if dam operations under the new ROD, daily and experimental flows, have the expected result of "more native plant community cover, higher native plant diversity, a higher ratio of native to nonnative plants, less arrowweed, and more wetland," (VanderKooi and others, 2017). This project utilizes annual field measurements (Element 1) and digital imagery (Element 2) for integrated monitoring of changes in vegetation at river segment (for example Glen Canyon, Marble Canyon, etc.) and system-wide scales. Included in monitoring are a 5-year assessment of vegetation change (Element 1) and an analysis of a new system-wide remote sensing vegetation classification for, providing an assessment of tamarisk beetle defoliation from 2009-2013 and sand/vegetation turnover dynamism (Element 2). Each of these products provides an assessment of the status of plant communities identified as being of interest or concern by stakeholders. Elements 1 and 2 are complementary methods of vegetation monitoring that determine status and trends at different spatial and temporal scales (Palmquist and others, in press). These two elements will be integrated through an assessment of relations between fine-scale, ground-based monitoring with the coarser-scale, spatially continuous remotely-sensed data. This assessment will allow us to identify the appropriate frequency of the ground-based monitoring (annual, biennial, or otherwise) and to integrate ecological processes occurring across different spatial and temporal scales.

Element 3 proposes to analyze vegetation data from Elements 1 and 2, existing historic vegetation data, and flow data to examine the influence of dam operations and other environmental variables on riparian vegetation distribution and address other knowledge gaps regarding vegetation response. A recent knowledge assessment that was conducted to identify the current understanding of vegetation response to dam operations elucidated uncertainties regarding how daily flows and experimental flows impact vegetation complexity, functional diversity, and species composition. We plan to address some of these uncertainties by creating predictive models of vegetation responses to LTEMP flow scenarios based on the vegetation monitoring and remote-sensing products outlined above (and described below). These predicted outcomes will be generated across multiple spatial scales in order to better understand how experimental flows are impacting the integrity of riparian vegetation. The results of this work will help predict vegetation response to dam operations outlined in the LTEMP, help assess if the LTEMP management goals for vegetation are advancing, and inform the parameters in which vegetation management will be most successful.

As stated in the LTEMP ROD, NPS and tribal partners will coordinate with GCMRC to conduct targeted vegetation removal and plantings, including "control of nonnative plant species and revegetation with native species (U.S. Department of Interior, 2016)." Project element 4 will help address information needs and management design required for the successful implementation of this required vegetation management. The NPS, Tribes, and other stakeholders will also seek to preserve sand resources, camp sites, and archeological sites through vegetation removals, restore native riparian plants by planting native species, and control exotic plants. The long-term success of planting efforts will depend on matching genetically suitable plant material to specific sites varying in substrate stability and existing vegetation. Monitoring of post-removal vegetation trajectories could identify how successional processes interact with dam operations, determine methods for the long-term preservation of these sites, and prioritize needs for future interventions on a site-by-site basis. These sites will encompass only a small portion of the riparian corridor and will have different goals and locations from the monitoring outlined in Elements 1 and 2, so this work cannot replace ongoing monitoring efforts throughout the CRe.

3. Hypotheses and Science Questions

The proposed work in this project is divided into four project elements. The first three elements are individually and collectively addressing a suite of science questions, whereas the fourth element provides decision support for vegetation management. The main scientific questions that the first three project elements are designed to answer are:

C.1. From site-scale, ground-based monitoring:

- What is the status (composition and cover) of native and non-native vascular plant species within the riparian zone of the Colorado River from Glen Canyon Dam and to 240 river miles downstream of Lees Ferry?
- What are the changes in vegetation composition and cover in the riparian zone, as related to geomorphic setting and dam operations, particularly flow regime.

C.2. From landscape-scale remote sensing:

- How does the composition of woody riparian vegetation vary spatially throughout the entire river corridor, and how have species have changed through time in comparison to previous classification?
- Where and how much turnover between bare sand and riparian vegetation occurs due to erosion, deposition, establishment, and mortality within the stages of the riparian zone currently inundated by HFEs and other flow fluctuations?
- Where have tamarisk beetle herbivory events and tamarisk mortality occurred in the river corridor since the 2013 remote sensing overflight?

C.3. From analysis and modelling that synthesizes site- and landscape-scale, ground- and remote sensing monitoring:

- Which environmental stressors have the strongest effect on species composition and location and at what scales?
- Can predictive models of how LTEMP flows will alter vegetation be developed that provide a much better understanding than the simple models developed for the EIS?

C.4.:

- How should vegetation treatments be designed and evaluated in order to best: quantify restoration goals and achievements; identify experimental sites and treatments that will balance desired outcomes with information gain; leverage information on appropriate transfer zones for native plant materials.

4. Background

Riparian vegetation is strongly influenced by seasonal and interannual discharge such that changes to the flow regime alter the plant species that can reproduce and survive (Naiman and Decamps, 1997; Rood and others, 2003). Changes in discharge fundamentally change the structure and function of the associated riparian vegetation, whether that change is from a natural to a regulated flow regime or among differing regulated flow regimes (Greet and others, 2011; Lytle and Poff, 2004; Rood and others, 2003; Shafroth and others, 2002; Stromberg, 2001). Daily flow patterns and flow experiments designed to influence fish, food base, or sediment will therefore have a collateral influence on riparian vegetation, even if vegetation is not removed in the process since flooding and drought can alter the structure and types of vegetation (Greet and others, 2011; Lytle and Poff, 2004). Since riparian plants have different societal, biological, and physical values (e.g., tall shade trees vs. thorny herbs), changes to the amount and types of vegetation impact the quality of wildlife habitat (Merritt and Bateman, 2012; Ralston, 2005), influence sediment deposition and retention (Dean and Schmidt, 2011; Manners and others, 2014), affect the experience of visitors (Ralston, 2005; Stewart and others, 2003), and influence ecological integrity in general (Bailey and others, 2001; Richardson and others, 2007; Stromberg and others, 2012). Thus, current and future dam operations as part of the LTEMP ROD alter riparian vegetation and affect the following resource goals:

- *Riparian vegetation*: Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.
- *Natural processes*: Restore, to the extent practicable, ecological patterns and processes within their range of natural variability, including the natural abundance, diversity, and genetic and ecological integrity of the plant and animal species native to those ecosystems.
- *Recreational experience*: Maintain and improve the quality of recreational experiences for the users of the CRe.
- *Tribal resources*: Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.

Regular monitoring of the native to non-native plant species ratio, species richness, and overall location and types of vegetation that occur in the CRe is the best way to assess whether or not the resource goals for riparian vegetation are being met. Since riparian vegetation in the CRe is layered and complex (for example, >300 different species ranging from annual species that are only a few centimeters tall to hundred year old trees over 20m tall), it is best practice to monitor on both annual and decadal-scale time scales to observe both rapid changes (e.g., shifts in wetland communities) and slower changes such as tree growth and mortality (e.g., impacts of the herbivorous tamarisk beetle born out over many growing seasons). It is also important to sample at multiple spatial scales and geographic extents, and to monitor locations along the entire length of the corridor, since riparian vegetation communities change with distance downstream. The different floristic communities located along the river may not respond similarly to dam operations, so conclusions based on data from one end of the canyon (for example, Marble Canyon) cannot be applied to another part of the canyon (for example, western Grand Canyon). The combination of Elements 1 (ground-based monitoring) and 2 (digital imagery) allow an assessment of how dam operation are altering riparian vegetation at both the short- and long-time scales, as well as at fine- and broad- spatial scales across the geographic extent of the influence of dam operations. Element 3 utilizes monitoring data (synthesis and analysis) from Elements 1 & 2 to support adaptive management, while Element 4 draws on the data and analysis from Elements 1 – 3 to assist with the planning and development of experimental vegetation treatments.

5. Proposed Work

5.1. Project Elements

Project Element C.1. Ground-based riparian vegetation monitoring

Brad Butterfield, Research Assistant Professor, Northern Arizona University
Emily Palmquist, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element is annual ground-based monitoring conducted at the species level, and includes collecting data at stratified random sample sites between GCD and RM 240. These data provide an overall assessment of the status and trends of vegetation composition, cover, richness, and native to nonnative species dominance through time across the three main geomorphic features along the river; sandbars, debris fans, and channel margins (e.g., differences in functional group composition along the river, Figure 1) (Palmquist and others, *in press*). Ground-based monitoring is particularly useful for studying the entire suite of plant species that occur in the riparian area, including forbs, grasses, and shrubs. This method of monitoring vegetation is complemented by vegetation classification products derived from the digital imagery (Element 2). The current monitoring protocol began in 2013 and has been continued annually since then (Palmquist and others, *in press*). The primary purpose of this monitoring project is to quantify the composition and cover of riparian vegetation in order to determine the status of native vegetation throughout the experimental flows planned for the next 20 years, such that the vegetation is, "diverse, healthy, productive, self-sustaining, and ecologically appropriate" (U.S. Department of Interior, 2016). These data can additionally be used to assess vegetation characteristics that affect recreational experience (e.g., is there an increase in thorny vegetation on sandbars?) and potentially inform wildlife habitat quality and availability. Particularly, this element aims to:

1) Annually sample and summarize the status (composition and cover) of native and non-native vascular plant species within the riparian zone of the Colorado River from GCD and to 240 river miles downstream of Lees Ferry.
2) At 5-year intervals, assess change in vegetation composition and cover in the riparian zone, as related to geomorphic setting and dam operations, particularly flow regime.
3) Use available data to assess the required frequency for ground-based monitoring (i.e., power analysis).
4) Collect data in a manner that can be used by multiple stakeholders and is compatible with the basin-wide monitoring programs overseen by the NPS's Northern Colorado Plateau Network Inventory and Monitoring program.

This project element is independent of and can inform the experimental vegetation management work that is being planned by NPS and tribal stakeholders with science support from GCMRC per the LTEMP ROD (Element 4, below). The experimental vegetation management that is planned under the ROD will only affect a small portion of the river corridor (approximately <1%), so it is necessary to continue monitoring the riparian corridor as a whole in order to assess if goals for this resource are being met.

Ground-based riparian monitoring utilizes both stratified random sampling and sites that are revisited each year. The combination of a random sample design and a revisit design allows us to understand changes that are occurring along the whole length of the mainstem by sampling a relatively small portion of the area. The random sample dataset encompasses approximately 70 to 90 sample sites each year distributed among channel margins, debris fans, and sandbars between RM -15.5 and 240, in order to gain a broad-scale understanding of how riparian vegetation responds to variability in hydrology and other factors across multiple habitats and in all reaches. These data can then be used to identify variability in vegetation composition and structure in order to detect impacts of dam operations on riparian vegetation. The dataset based on annual site revisits is collected on annually surveyed sandbars (see project B.1) and is intended to provide information on how vegetation is impacting sand deposition and retention, as well as how the changing physical processes of sandbars influence vegetation encroachment.

Collaborations with the Northern Colorado Plateau Network Inventory and Monitoring program will continue. This group currently monitors riparian vegetation along the Yampa River, the Green River, and the upper Colorado River. This collaboration focuses on coordinating data collection methods and techniques with the ultimate goal of being able to conduct basin-wide analyses of riparian vegetation change across river systems with varying levels of hydrologic alteration using our combined datasets. This collaboration also fosters communication and positive relationships with the National Park Service and the riparian ecology scientific community.

Five years of data using the current monitoring protocol will be available after the 2017 field season, which is a reasonable time frame to begin assessing the status and trends of riparian vegetation in the CRe. This project element will include a summary of data collected from 2013 through 2017 with a particular focus on the state of riparian vegetation at the beginning of the new ROD. It will also include an assessment of interannual variation and correlation with data from Element 2 in order to determine how often riparian vegetation should be sampled to sufficiently track its status and trends (i.e., power analysis), and what kinds of complementary information these two types of data provide. Since previous ground-based vegetation monitoring data is only available from the 1990's and early 2000's, the monitoring that started in 2013 will reflect the current state of vegetation and is expected to be used as a baseline against which change correlated with daily flows and any implemented management flows (spring HFEs, trout management flows, etc.) can be assessed. It may also indicate the current trajectory of riparian vegetation, e.g., if non-native species are increasing or decreasing and where or if sandbars support higher amounts of vegetation than other geomorphic features.

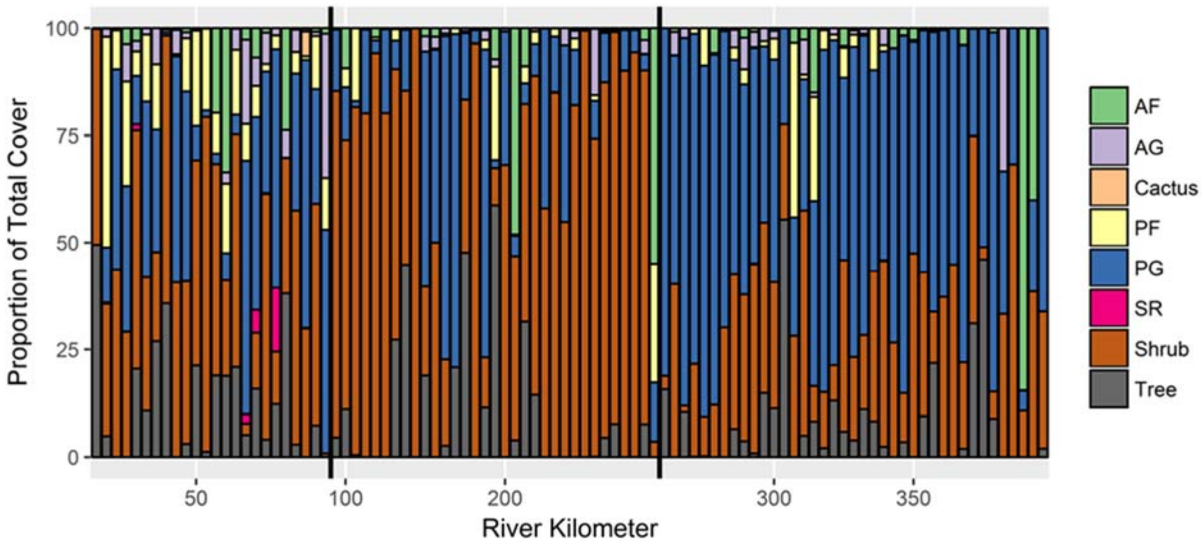

Figure 1. Proportions of the total cover of plant growth forms for each random sample site from 2014. Vertical bars represent one sample site and colors represent the proportion of each growth form. River segment boundaries are indicated by black, vertical lines at Rkm 97 and 259. Marble Canyon = Rkm 0 – 97, eastern Grand Canyon = Rkm 97 – 259, western Grand Canyon = Rkm 259 – 404. AF = annual forb, AG = annual grass, Cactus = cactus, PF = perennial forb, PG = perennial grass, SR = sedge/rush, Shrub = shrub, Tree = tree. [1 river kilometer (Rkm) = 0.6 river miles]

Project Element C.2. Imagery-based riparian vegetation monitoring at the landscape scale

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Durning, Research Specialist Sr., Northern Arizona University

Recently, landscape-scale remote sensing of riparian vegetation has been successfully used by GCMRC scientists to investigate several important contemporary environmental issues in the CRe. Specifically, we have: 1) quantified long-term changes in total riparian vegetation related to dam release patterns (discharge from the dam) and regional climate within specific reaches of the CRe (Sankey and others, 2015a), 2) classified and mapped the composition of total riparian vegetation by vegetation species and associations of the CRe (Sankey and others, 2016; Ralston and others, 2008), and 3) mapped non-native invasive tamarisk vegetation impacted by the introduced tamarisk beetle using 2009 and 2013 imagery in the entire CRe, as well as in Glen Canyon using the imagery and 2013 airborne LiDAR (Sankey and others, 2016). This project element will continue to leverage those successful applications of landscape-scale remote sensing of riparian vegetation to:

1) Analyze mapped species and associations to determine how the composition of woody riparian vegetation varies spatially throughout the entire river corridor and how species have changed through time as captured in digital imagery;
2) Quantify where, and to what degree, the combination of riparian vegetation encroachment and flow regime changes have altered bare sand area, and map turnover between riparian vegetation and bare sand due to erosion, deposition, establishment, and mortality;
3) Detect where tamarisk beetle herbivory events and tamarisk mortality have occurred since 2013 in the river corridor using interannual satellite imagery.

In (1) we will focus on interpreting the vegetation classification which is currently in production during FY2017 by the riparian vegetation remote sensing project using the 2013 multispectral image mosaic of the river corridor from GCD to Lake Mead (Durning and others, 2016). We will also complete a change detection of the most recent riparian vegetation classification with the previously produced classification of Ralston and others (2008), based on multispectral imagery acquired in 2002. With the change detection analysis we will, for the first time, be able to synoptically assess corridor-wide vegetation shifts at the species and community levels for woody, long-lived species. We will better understand vegetation succession that has occurred during that past 2 decades, including transitions from herbaceous (in general) to woody species that may be contributing to factors like bank stabilization, channel narrowing, and campsite encroachment. We will also be able to compare decadal-scale species- and association-level monitoring from remote sensing with ground-based monitoring to better understand what kinds of complementary information the two types of data provide.

In (2) we will synthesize existing overflight imagery and bathymetric remote sensing data derived since 2002 that describe the extent of vegetation and bare sand, as well as modelled flow inundation (Durning et al., 2016, 2017a, b; Kaplinski et al., 2017; Kasprak, 2017; Magirl et al., 2008; Sankey et al., 2015a,b) to analyze the past role of vegetation extent and river discharge in affecting the areal extent of bare sand. We will use methods recently described by Kasprak (2017) and we will focus on the segment of the river from Glen Canyon Dam to Bright Angel Creek (approximately 105 RM) for which river channel substrate classifications have been produced. We will additionally predict how the extent of bare sand will continue to change over the next 20 years under the LTEMP ROD. As part of this work, we will analyze the amount of turnover or ‘dynamism’ that has occurred between riparian vegetation and bare sand within the river corridor. Sankey and others (2015a) determined that HFEs in general do not keep vegetation from expanding onto bare sand habitat, but a synoptic assessment of sand-vegetation turnover for a large segment of the river corridor has not been completed. A full assessment will identify the types of riparian vegetation, the inundation zones, and the geomorphic landform units for which turnover currently occurs, as well as the magnitude of turnover. In (3) we will use interannual time series of World View satellite imagery to detect beetle-impacted tamarisk mapped with imagery from 2013 that have subsequently experienced new or additional beetle herbivory events and eventual mortality. This work will focus on specific reaches of the river where the canyon is wide enough to be suitable for satellite image analysis.

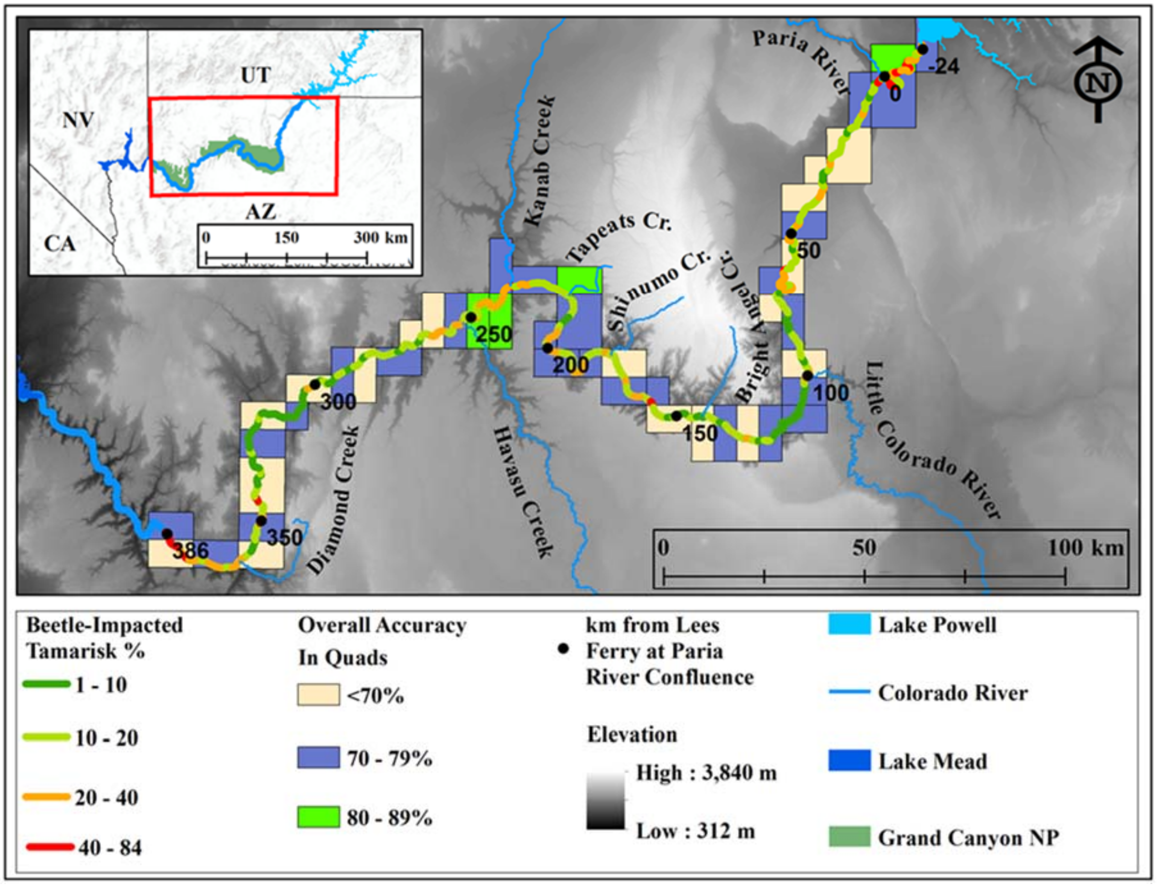

Figure 2. Map of proportion (in percent) of tamarisk impacted by the tamarisk beetle within 1-mile river segments in the river corridor from GCD to Lake Mead. Map also shows the estimated accuracy of the remote sensing classification of tamarisk by image quad. Element 2 will use these data produced in the FY2015-17 work plan with interannual satellite image analysis to map beetle-induced tamarisk mortality.

Project Element C.3. Vegetation responses to LTEMP flow scenarios

Brad Butterfield, Northern Arizona University
Emily Palmquist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Predictive models of riparian vegetation change in response to LTEMP flow scenarios can inform stakeholders about the potential influences of daily flows and alternative flows outlined in the LTEMP ROD (e.g., trout management flows, spring high flow events, bug flows, equalization flows) on this resource of concern. This element will utilize existing vegetation data (from Elements 1 and 2, as well as historic data) and flow data integrated with flow-response vegetation guilds to examine the influence of flow scenarios on species distributions and potential community change (Figure 3). The modeling done for the EIS identified likely outcomes for plant community states, but at a basic level of presence or absence and expansion or contraction. This modeling provides more detail, potentially about specific species of interest to stakeholders, and will result in a much better understanding of how dam operations change vegetation. We will test these predictions based on responses observed in long-term monitoring data to a wealth of hydrological and geomorphological factors. The results of this work will help inform the assessment of how ground-based sampling and data derived from the digital imagery can be most efficiently integrated (Elements 1 and 2) and help inform the implementation of experimental vegetation treatments (Element 4).

Models of how flow regime impacts the distribution and composition of riparian vegetation are useful for developing successful experimental vegetation treatments and can inform the planning outlined in Element 4 (Stromberg, 2001). Ecological rehabilitation is expensive and time consuming, so an understanding of what environmental factors are influencing the growth and survival of different species is imperative to increasing chances of a successful treatment. For example, if the goal of vegetation treatment is to increase the cover of native plant species, it is valuable to know if the current composition of species is largely due to flow regime or other environmental factors, such as shade, soil composition, temperature, or precipitation. If the latter has a stronger influence on riparian vegetation composition, then treatment design should primarily focus on planting in areas that have the correct temperature, light availability, and sand: silt ratio. If the former has a stronger influence, then the placement of plantings in relation to the river is a much more important consideration, and may require some creative solutions to supporting vegetation that struggles with the given flow regime. The objectives of this project element then are to use existing data to:

1) Develop predictive models of how LTEMP flows will alter vegetation that provide a much better understanding than the simple models developed for the EIS,
2) Determine which environmental stressors have the strongest effect on species composition and location and at what scale,
3) Use that knowledge to support the design of vegetation treatments (Element 4).

Numerous vegetation datasets have been collected over the past two decades in the CRe, which can be used to develop and test these models. Remotely sensed imagery (Element 2), plot-based monitoring (Element 1) and functional trait data have culminated in a number of synthetic analyses during the previous work plan, including changes in the cover and structure of vegetation (Sankey and others, 2015a), state and transition models of vegetation change (Ralston and others, 2014), flow-response guilds (Merritt and others, 2010), and mechanistic links between plant functional traits and inundation (McCoy-Sulentic and others, 2017a; McCoy-Sulentic and others, 2017b). These data and analyses provide a robust framework for developing predictive vegetation models, which hitherto have been overly simplistic and have not incorporated the many complexities that influence riparian vegetation. That simplicity reduced the usefulness of the models, and incorporating as much of the data as we have available will greatly improve our predictive power and help understand the mechanisms underlying vegetation community assembly. These more complex models will allow us to model how sediment accumulation and loss on sandbars interacts with vegetation and how environmental variables differentially influence vegetation in the changing setting of LTEMP dam operations. No previous modeling efforts have been able to tackle these topics, due to limitations to model complexity. These models will also support the design of successful vegetation treatments implemented per the LTEMP ROD (Element 4) by identifying the primary limiting factors for riparian vegetation establishment and predicting the influence of experimental flows (trout management flows, macroinvertebrate production flows, etc.) on riparian vegetation (Webb and others, 2014).

We propose to use hierarchical Bayesian modeling to generate these models (Webb and others, 2014). Briefly, hierarchical Bayesian models can be used to couple empirical statistical analysis with process-based, theoretical models of systems derived from quantitative review of literature and expert opinion. The "hierarchical" aspect of this analysis includes the ability to incorporate ecological processes functioning at varying scales, which is ideal for the CRe in which both temporal (HFEs, seasonal, and daily variation) and spatial (reach, sand bar-eddy complex, micro-elevation) variation in ecological processes is structured in clear hierarchies. The "Bayesian" aspect of this analysis incorporates prior information derived from process-based models that improves predictive ability and, critically, is designed for predicting future outcomes and associated uncertainty under simulated conditions. To generate alternative dam operations, we will draw from the current ROD to predict if the planned operations for the next 20 years will result in a departure from the goals for riparian vegetation on sandbars, for wildlife habitat, and as it relates to vegetation management.

Depending on the timing and availability of data generated as a part of Element 4 (see below), genetic and plasticity (ability to change its growth and shape in response to the environment) data from key riparian plant species may be incorporated into the final models. Genetic diversity and plasticity can factor strongly into the resilience and resistance of vegetation treatments and ecosystems to environmental change, but these are as yet an understudied components of the CRe. If we are able to incorporate these data into the models, we should be able to examine the roles that these factors play in mediating plant and vegetation responses to variation in flows.

Figure 3. Riparian vegetation along the Colorado River can vary greatly from place to place. On the left, a mix of dense grasses and Tamarix spp. grow at RM 42.9; very little bare ground is present. On the right, at RM 70.1 only two species are seen in this picture, both woody shrubs and lots of sand is exposed. Modeling species composition based on a suite of environmental factors, such as flow variables and substrate, can elucidate why different species grow in some places, but not others, and inform the experimental vegetation treatments.

Project Element C.4. Vegetation management decision support

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Emily Palmquist, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Durning, Research Specialist Sr., Northern Arizona University

The current LTEMP ROD (U.S. Department of Interior, 2016) includes a number of vegetation treatment actions to be conducted on NPS managed lands, in consultation with tribal partners and with science support from GCMRC. These experimental activities are expected to include; (1) control of nonnative plant species, (2) development of native plant materials, (3) replanting native plant species, (4) removal of vegetation encroaching on campsites, and (5) management to assist with cultural site preservation. This work is outlined in the BOR TWP C.7. Experimental Vegetation Treatment) and is being developed in consultation with GCMRC. The GCMRC plans to participate in meetings with both tribal and NPS partner in FY2018 to assist with planning and coordination. In addition to the objectives listed below, we anticipate contributing time, data, and expertise to both tribal and NPS partners as it is useful to them. Specifically, GCMRC will contribute to the planning and implementation process by:

1) Participating in planning meetings with tribal and NPS partners,
2) Assisting with the development of a repeatable process that managers can use to quantify restoration goals and achievements and identify an initial set of experimental sites and treatments that will balance desired outcomes with information gain,
3) Providing information on appropriate transfer zones for native plant materials,
4) Assisting with monitoring plan and protocol development,
5) Designing and helping implement pilot vegetation management projects.

Success of vegetation treatments that incorporate native plantings is likely to depend, in large part, on the availability and use of genetically suitable native plant materials (Durka and others, 2017; Grady and others, 2011; Pluess and others, 2016). The genetic make-up of planted materials affects how well individuals grow and survive in a treatment location and has cascading effects on the ecological integrity of the riparian system (Crutsinger and others, 2014; Grady and others, 2011; Whitham and others, 2012). Transfer zones based on existing genetic structure and morphological characteristics, which indicate where restoration stock should come from, are now considered “best practices” for determining ecologically appropriate source populations that balance local-adaptation, genetic diversity, and ecosystem services (Durka and others, 2017; Jørgensen and others, 2016; Williams and others, 2014). The LTEMP Scientific Monitoring Plan indicates that one aspect of the experimental vegetation treatments will include “establishing sources of native plants” (VanderKooi and others, 2017), illustrating the importance of this step in the management process. The NPS restoration approaches use local materials in rehabilitation treatments in order to retain locally adapted genotypes and conserve unique local populations. However, the extent and parameters of what “local” means in the CRe and in riparian systems in general is unknown.

Grand Canyon National Park, in coordination with GCMRC, has recently provided separate funding to support molecular genetic laboratory work at Northern Arizona University which will provide the data necessary to develop genetically appropriate transfer zones. GCMRC will work with the NPS and tribal partners to identify appropriate planting material of several focal native species to be grown in greenhouses for use in experimental revegetation treatments. This collaboration can also be extended to assisting with choosing appropriate locations for vegetation management and designing planting plans, as needed. We intend to seek outside funding to supplement genetic data with greenhouse experiments conducted in cooperation with the Restoration Assessment and Monitoring Program for the Southwest (RAMPS, http://nau.edu/Merriam-Powell/RAMPS/), and in consultation with tribal resource managers and federal partners. These experiments would be aimed at understanding variation in important traits associated with drought and inundation tolerances, competitive ability and other factors to help develop protocols for plant materials development that will maximize the effectiveness of revegetation treatments.

Targeted monitoring will be necessary in order to properly assess the efficacy and secondary consequences of experimental vegetation treatment but could be developed in such a way that this monitoring supplements the information gained from Elements 1 and 2, while simultaneously assessing the success of vegetation treatments. Protocols may vary depending upon treatment type, but are likely to include assessments of plant regrowth and plant community changes in removal treatments, plant growth and survival in native plantings, and associated changes in the physical environment such as sand fluxes. GCMRC will develop protocols that are necessary to assess whether treatments are deemed effective based on desired outcomes defined by NPS and tribal partners.

Lastly, these collaborations and assessment can be used to develop a flexible decision support tool to provide managers (tribal resource managers, federal partners) with treatment recommendations given information on target locations and desired outcomes. Recommendations will provide a range of success probabilities given hydrological settings, flow levels, timing of treatments, focal species and native plant material sources (genotypes or cultivars). The decision support tool will be tested using a range of preliminary and simulated data, with the intent of populating the tool with experimental data as they are obtained. This tool will utilize an existing platform currently under development by RAMPS.

5.2. Deliverables

Element C.1: FY2018: presentation of database development, including digitization of records from the 1990s to early 2000s at GCMRC's Annual Reporting Meeting (Jan. 2019); FY2019: peer-reviewed manuscript of status and trends of riparian vegetation from 2013-2017 and presentation of status and trends at GCMRC's Annual Reporting Meeting; FY2020: USGS open-file report on assessment of appropriate frequency for vegetation monitoring and presentation of vegetation monitoring recommendations at GCMRC's Annual Reporting Meeting

Element C. 2: FY2018: presentation of aerial image-based vegetation classification at GCMRC’s Annual Reporting Meeting (Jan. 2019); FY2018: presentation of bare sand and riparian vegetation dynamism at GCMRC’s Annual Reporting Meeting (Jan. 2019), peer-reviewed manuscript on bare sand and riparian vegetation dynamism. FY2020: peer-reviewed journal manuscripts describing (i) the aerial image-based vegetation classification and (ii) satellite image analysis of tamarisk phenology and beetle impacts.

Element C.3: FY2018: Peer-reviewed journal manuscripts describing the relative influences of environmental pressures, including flow regime, on the composition and location of riparian vegetation (i) along multiple riparian features throughout the canyon and (ii) detailed predicted suitable habitat on sand bars, which will also be presented at GCMRC's Annual Reporting Meeting; FY2019: Peer-reviewed journal manuscript on vegetation feedbacks to sandbars and an associated decision-support tool for predicting impacts of flow regime on vegetation composition and species of interest, made available to all stakeholders via the web, which will also be presented at GCMRC's Annual Reporting Meeting (Jan. 2020); FY2020: Peer-reviewed journal manuscript describing biotic and environmental controls on potential vegetation treatment success and presentation of results at GCMRC's Annual Reporting Meeting (Jan. 2021).

Element C.4: FY2018: White paper developed in conjunction with stakeholders describing vegetation treatment objectives, approaches and monitoring protocols, presented at GCMRC's Annual Reporting Meeting (Jan. 2019); FY2019: Peer-reviewed manuscript of provisional transfer zones for native plant propagation and planting, which will be presented at GCMRC's Annual Reporting Meeting (Jan. 2020); FY2020: Decision support tool for vegetation treatment recommendations made available to all stakeholders via the web, and presented at GCMRC's Annual Reporting Meeting (Jan. 2021).

6. References

Bailey, J.K., Schweitzer, J.A., and Whitham, T.G., 2001, Salt cedar negatively affects biodiversity of aquatic macroinvertebrates: Wetlands, v. 21, no. 3, p. 442-447, http://dx.doi.org/10.1672/0277-5212(2001)021[0442:SCNABO]2.0.CO;2.

Crutsinger, G.M., Rudman, S.M., Rodriguez-Cabal, M.A., McKown, A.D., Sato, T., MacDonald, A.M., Heavyside, J., Geraldes, A., Hart, E.M., LeRoy, C.J., and El-Sabaawi, R.W., 2014, Testing a 'genes-to-ecosystems' approach to understanding aquatic–terrestrial linkages: Molecular Ecology, v. 23, no. 23, p. 5888-5903, http://dx.doi.org/10.1111/mec.12931.

Dean, D.J., and Schmidt, J.C., 2011, The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region: Geomorphology, v. 126, no. 3-4, p. 333-349, http://dx.doi.org/10.1016/j.geomorph.2010.03.009.

Durka, W., Michalski, S.G., Berendzen, K.W., Bossdorf, O., Bucharova, A., Hermann, J.-M., Hölzel, N., and Kollmann, J., 2017, Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration: Journal of Applied Ecology, v. 54, no. 1, p. 116-126, http://dx.doi.org/10.1111/1365-2664.12636.

Durning, L.E., Sankey, J.B., Davis, P.A., and Sankey, T.T., 2016, Four-band image mosaic of the Colorado River corridor downstream of Glen Canyon Dam in Arizona, derived from the May 2013 airborne image acquisition: U.S. Geological Survey Data Series 1027, https://doi.org/10.3133/ds1027.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, T.T., 2017a, Riparian vegetation classification of the Colorado River Corridor, Grand Canyon, Arizona, 2013—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7K64GJF.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, T.T., 2017b, Water classification of the Colorado River Corridor, Grand Canyon, Arizona, 2013—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7PZ5799.

Grady, K.C., Ferrier, S.M., Kolb, T.E., Hart, S.C., Allan, G.J., and Whitham, T.G., 2011, Genetic variation in productivity of foundation riparian species at the edge of their distribution—Implications for restoration and assisted migration in a warming climate: Global Change Biology, v. 17, no. 12, p. 3724-3735, http://dx.doi.org/10.1111/j.1365-2486.2011.02524.x.

Greet, J., Webb, J.A., and Downes, B.J., 2011, Flow variability maintains the structure and composition of in-channel riparian vegetation: Freshwater Biology, v. 56, no. 12, p. 2514-2528, http://dx.doi.org/10.1111/j.1365-2427.2011.02676.x.

Jørgensen, M.H., Elameen, A., Hofman, N., Klemsdal, S., Malaval, S., and Fjellheim, S., 2016, What's the meaning of local? Using molecular markers to define seed transfer zones for ecological restoration in Norway: Evolutionary Applications, v. 9, no. 5, p. 673-684, http://dx.doi.org/10.1111/eva.12378.

Kaplinski, M., Hazel Jr., J.E., Grams, P.E., Kohl, K., Buscombe, D.D., and Tusso, R.B., 2017, Channel mapping river miles 29-62 of the Colorado River in Grand Canyon National Park, Arizona, May 2009: U.S. Geological Survey Open-File Report, http://doi.org/10.3133/ofr20171030.

Kasprak, A., Buscombe, D., Caster, J, East, A, Grams, P., Fairley, H., Sankey, J.B., 2017. The Individual and Additive Effects of Hydrologic Alteration and Vegetation Encroachment on Sediment Connectivity in Grand Canyon. Presentation to the Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 24th 2017, Phoenix, AZ. https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR6_Kasprak.pdf

Kearsley, M.J.C., and Ayers, T.J., 1996, The effects of interim flows from Glen Canyon Dam on riparian vegetation in the Colorado River corridor, Grand Canyon National Park, Arizona—final report: Flagstaff, Northern Arizona University, submitted to Grand Canyon National Park, Grand Canyon Science Center, cooperative agreement no. 8041-8-0002, 702 p., http://www.gcmrc.gov/library/reports/biological/Terrestrial/Kearsley/Kearsley1996b.pdf.

Lytle, D.A., and Poff, N.L., 2004, Adaptation to natural flow regimes: Trends in Ecology and Evolution, v. 19, no. 2, p. 94-100, http://dx.doi.org/10.1016/j.tree.2003.10.002.

Magirl, C., Breedlove, M.J., Webb, R.B., and Griffiths, P.G., 2008, Modeling Water-Surface Elevations and Virtual Shorelines for the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey, Scientific Investigations Report 2008–5075: 1–32., available at https://pubs.er.usgs.gov/publication/sir20085075.

Manners, R.B., Schmidt, J.C., and Scott, M.L., 2014, Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river—Results from a natural field-scale experiment: Geomorphology, v. 211, p. 100-115, http://dx.doi.org/10.1016/j.geomorph.2013.12.033.

McCoy-Sulentic, M.E., Kolb, T.E., Merritt, D.M., Palmquist, E., Ralston, B.E., Sarr, D.A., and Shafroth, P.B., 2017a, Changes in community-level riparain plant traits over inundation gradients, Colorado River, Grand Canyon: Wetlands, p. 1-12, available at http://dx.doi.org/10.1007/s13157-017-0895-3.

McCoy-Sulentic, M.E., Kolb, T.E., Merritt, D.M., Palmquist, E.C., Ralston, B.E., and Sarr, D.A., 2017b, Variation in species-level plant functional traits over wetland indicator status categories: Ecology and Evolution, p. 1-13, available at http://dx.doi.org/10.1002/ece3.2975.

Merritt, D.M., and Bateman, H.L., 2012, Linking stream flow and groundwater to avian habitat in a desert riparian system: Ecological Applications, v. 22, no. 7, p. 1973-1988, http://dx.doi.org/10.1890/12-0303.1.

Merritt, D.M., Scott, M.L., Poff, N.L., Auble, G.T., and Lytle, D.A., 2010, Theory, methods and tools for determining environmental flows for riparian vegetation—Riparian vegetation-flow response guilds: Freshwater Biology, v. 55, no. 1, p. 206-225, http://dx.doi.org/10.1111/j.1365-2427.2009.02206.x.

Naiman, R.J., and Decamps, H., 1997, The ecology of interfaces—Riparian zones: Annual Review of Ecology and Systematics, v. 28, p. 621-658, http://dx.doi.org/10.1146/annurev.ecolsys.28.1.621

Palmquist, E.C., Ralston, B.E., Sarr, D.A., and Johnson, T.C., *in press*, Monitoring riparian vegetation composition and cover along the Colorado River downstream of Glen Canyon Dam: U.S. Geological Survey Techniques and Methods.

Pluess, A.R., Frank, A., Heiri, C., Lalagüe, H., Vendramin, G.G., and Oddou-Muratorio, S., 2016, Genome–environment association study suggests local adaptation to climate at the regional scale in *Fagus sylvatica*: New Phytologist, v. 201, no. 2, p. 589-601, http://dx.doi.org/10.1111/nph.13809.

Ralston, B.E., 2005, Riparian vegetation and associated wildlife, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 103-121 p., http://pubs.usgs.gov/circ/1282/.

Ralston, B.E., Davis, P.A., Weber, R.M., and Rundall, J.M., 2008, A vegetation database for the Colorado River ecosystem from Glen Canyon Dam to the western boundary of Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008-1216, 37 p., http://pubs.usgs.gov/of/2008/1216/.

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.

Richardson, D.M., Holmes, P.M., Esler, K.J., Galtowitsch, S.M., Stromberg, J.C., Kirkman, S.P., Pysek, P., and Hobbs, R.J., 2007, Riparian vegetation—Degredation, alien plant invasions, and restoration prospects: Diversity and Distributions, v. 13, no. 1, p. 126-139, http://dx.doi.org/10.1111/j.1366-9516.2006.00314.x.

Rood, S.B., Gourley, C.R., Ammon, E.M., Heki, L.G., Klotz, J.R., Morrison, M.L., Mosley, D., Scoppettone, G.G., Swanson, S., and Wagner, P.L., 2003, Flows for floodplain forests—Successful riparian restoration: BioScience, v. 53, no. 7, p. 647-56, http://people.uleth.ca/~rood/RoodlBioScience2003.PDF.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015a, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, http://dx.doi.org/10.1002/2015JG002991.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015b, Riparian vegetation, Colorado River, and climate: Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7J67F0P.

Sankey, T.T., Sankey, J.B., Horne, R., and Bedford, A., 2016, Remote sensing of tamarisk biomass, insect herbivory, and defoliation—Novel methods in the Grand Canyon region, Arizona: Photogrammetric Engineering and Remote Sensing, v. 82, no. 8, p. 645-652, https://doi.org/10.14358/PERS.82.8.645.

Schmidt, J.C., and Grams, P.E., 2011, The high flows—Physical science results, *in* Melis, T.S., ed., Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, p. 53-91, http://pubs.usgs.gov/circ/1366/.

Shafroth, P.B., Stromberg, J.C., and Patten, D.T., 2002, Riparian vegetation response to altered disturbance and stress regimes: Ecological Applications, v. 12, no. 1, p. 107-123, http://dx.doi.org/10.1890/1051-0761(2002)012[0107:RVRTAD]2.0.CO;2.

Stevens, L.E., Schmidt, J.C., Ayers, T.J., and Brown, B.T., 1995, Flow regulation, geomorphology, and Colorado River marsh development in the Grand Canyon, Arizona: Ecological Applications, v. 5, no. 4, p. 1025-1039, http://dx.doi.org/10.2307/2269352.

Stewart, W., Larkin, K., Orland, B., and Anderson, D., 2003, Boater preferences for beach characteristics downstream from Glen Canyon Dam, Arizona: Journal of Environmental Management, v. 69, no. 2, p. 201-211, http://dx.doi.org/10.1016/j.jenvman.2003.08.001.

Stromberg, J.C., 2001, Restoration of riparian vegetation in the southwestern United States—Importance of flow regimes and fluvial dynamism: Journal of Arid Environments, v. 49, no. 1, p. 17-34, http://dx.doi.org/10.1006/jare.2001.0833.

Stromberg, J.C., Andersen, D.C., and Scott, M.L., 2012, Riparian floodplain wetlands of the arid and semiarid southwest, *in* Batzer, D.P., and Baldwin, A.H., eds., Wetland habitats of North America—Ecology and conservation concerns: Berkeley, University of California Press, p. 343-356.

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p., http://pubs.usgs.gov/pp/1132/report.pdf.

Turner, R.M., Webb, R.H., Bowers, J.E., and Hastings, J.R., 2003, The changing mile revisited—An ecological study of vegetation change with time in the lower mile of an arid and semiarid region: Tucson, University of Arizona Press.

U.S. Department of the Interior, 1996, Record of Decision—Operation of Glen Canyon Dam Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Glen Canyon Dam Adaptive Management Program, 15 p., http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Yackulic, C.B., Schmidt, J.C., and Sankey, J.B., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

Webb, J.A., de Little, S.C., Miller, K.A., Stewardson, M.J., Rutherfurd, I.D., Sharpe, A.K., Patulny, L., and Poff, L.R.N., 2014, A general approach to predicting ecological responses to environmental flows—Making best use of the literature, expert knowledge, and monitoring data: River Research and Applications, v. 31, no. 4, p. 505-514, http://dx.doi.org/10.1002/rra.2832.

Webb, R.H., 1996, Grand Canyon—A century of change—Rephotography of the 1889-1890 Stanton expedition: Tucson, University of Arizona Press, 290 p.

Webb, R.H., Belnap, J., Scott, M.L., and Esque, T.C., 2011, Long-term change in perennial vegetation along the Colorado River in Grand Canyon National Park (1889-2010): Park

Science, v. 28, no. 2, p. 83-87, https://www.nature.nps.gov/ParkScience/archive/PDF/Article_PDFs/ParkScience28(2)Summer2011_83-87_Webb_et_al_2822.pdf.

Webb, R.H., Boyer, D.E., and Turner, R.M., 2010, Repeat photography—Methods and applications in the natural sciences: Washington, D.C., Island Press.

Webb, R.H., Leake, S.A., and Turner, R.M., 2007, The ribbon of green—Change in riparian vegetation in the southwestern United States: Tucson, University of Arizona Press.

Whitham, T.G., Gehring, C.A., Lamit, L.J., Wojtowicz, T., Evans, L.M., Keith, A.R., and Smith, D.S., 2012, Community specificity—Life and afterlife effects of genes: Trends in Plant Science, v. 17, no. 5, p. 271-281, http://doi.org/10.1016/j.tplants.2012.01.005.

Williams, A.V., Nevill, P.G., and Krauss, S.L., 2014, Next generation restoration techniques—Applications and opportunities: Trends in Plant Science, v. 19, no. 8, p. 529-537, https://doi.org/10.1016/j.tplants.2014.03.011.

7. Budget

Project	Project Description	Fiscal Year 2018 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$114,608	$1,821	$3,000	$65,000	$8,500		$28,947	$221,877
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$118,502	$1,821	$1,000		$79,000		$21,244	$221,568
C.3	Vegetation responses to LTEMP flow scenarios		$1,821			$90,710		$3,005	$95,536
C.4	Vegetation management decision support	$37,706	$1,821					$6,149	$45,676
	Total C	**$270,817**	**$7,285**	**$4,000**	**$65,000**	**$178,210**	**$0**	**$59,345**	**$584,657**

Project	Project Description	Fiscal Year 2019 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$88,203	$685	$2,700	$61,000	$8,500		$39,928	$201,016
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$65,109	$685			$82,000		$19,566	$167,360
C.3	Vegetation responses to LTEMP flow scenarios		$685			$87,948		$2,817	$91,450
C.4	Vegetation management decision support	$19,493	$685					$5,246	$25,424
	Total C	**$172,806**	**$2,740**	**$2,700**	**$61,000**	**$178,448**	**$0**	**$67,557**	**$485,251**

Project	Project Description	Fiscal Year 2020 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$105,013	$425	$1,500	$40,000	$8,500		$38,459	$193,897
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$66,725	$425	$1,000		$84,000		$20,239	$172,389
C.3	Vegetation responses to LTEMP flow scenarios					$87,773		$2,633	$90,406
C.4	Vegetation management decision support							$0	$0
	Total C	**$171,738**	**$850**	**$2,500**	**$40,000**	**$180,273**	**$0**	**$61,331**	**$456,692**

8. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element C.(i). Marsh community changes

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Marshes are regionally rare vegetation communities that have attracted considerable interest from diverse stakeholders associated with the Grand Canyon. Marsh cover increased in the Grand Canyon following construction of the GCD: the increase in baseflows and reduction in flood frequency created moderately inundated silty and sandy substrates ideal for a wide range of marsh species (Stevens and others, 1995). The postdam period may be divided into two distinct periods of different reservoir release patterns: (1) the period between 1963 and 1991 when power-plant operations involved unrestricted hydro-peaking and when long-duration floods occurred between 1983 and 1986 and (2) the period after 1991 when the range of daily hydro-peaking was restricted and when short-duration controlled floods occurred in 1996, 2004, 2008, 2012, 2013, 2014, and 2016 (Bureau of Reclamation, 1996; Schmidt and Grams, 2011). Marsh vegetation communities were mapped and categorized by Stevens and others (1995) in 1991, the end of the first distinct period of release patterns. At that time, marshes had increased from 0.09 to 25 hectares due to the preceding increase in baseflows and reduction in flood frequency. It is currently unknown how the second time period, characterized by reduced hydropeaking, has altered marsh habitat. Vegetation studies conducted during the interim flows of the early 1990's indicated this unique habitat was drying up (Kearsley and Ayers, 1996), and recent observations suggest that marshes have changed in species composition and have been replaced by xeric phreatophyte vegetation, for example tamarisk (*Tamarix* spp.) and mesquite (*Prosopis glandulosa*).

Given the expectation that the new LTEMP operations will support more wetland vegetation than other alternatives (U.S. Department of Interior, 2016), stakeholder interest in marsh vegetation, and observed reductions in its extent within the Grand Canyon, we propose to conduct a reassessment of species composition and extent of marsh vegetation. We will use both remote sensing and ground-based monitoring data, as was done in Stevens and others (1995). Additionally, environmental niche models of dominant marsh species will be used to estimate impacts of future flow scenarios. The overall objectives of the project element are to:

1) Identify how total marsh area has changed (i.e., increased, decreased, or remained stable) since the completion of the Stevens and others, (1995) study;
2) Identify whether and how species composition in the marshes has changed, and if so, in what ways during the same time frame as (1)
3) Determine the state of marsh habitats at the beginning of the new LTEMP operations to be able to assess if Alternative D does, in fact, support more marsh vegetation at the end of the ROD.

Remote sensing analysis of changes in marsh coverage will utilize data from recent riparian vegetation classification and change detection conducted by GCMRC (Durning and others, 2016; Sankey and others, 2015; Sankey and others, 2016) to estimate temporal trends in marsh cover, frequency and patchiness. Stevens and others (1995) reported that as of 1991, there were "253 fluvial wet marshes (cattail/reed and horseweed/Bermuda grass) and 850 dry marshes (horsetail/willow) that occupied 25.0 ha (1%) of the 363 km mainstream riparian corridor between Lees Ferry and Diamond Creek". We plan to use more recent remote sensing data to update the census of wet and dry marshes and determine how their spatial extent, patchiness and frequency by river reach (*sensu* Stevens and others, 1995) have changed. Remote sensing data will primarily be the corridor-wide multispectral imagery and vegetation classifications from 2002 and 2013 overflights (Ralston and others, 2008), though we will also consider using aerial imagery from 2004, 2005, and 2009 multispectral datasets (see Sankey and others, 2015). Vegetation classifications completed with 2002 and 2013 imagery include a wetland class which we will use as a proxy for the wet marsh category mapped by Stevens and others (1995). Thus we will determine where wet marshes mapped in 1991 are not similarly mapped as the remotely sensed wetland class in 2002 and/or 2013. We will determined where and why areas might exist that were mapped as the wetland class in 2002 and/or 2013 but not similarly mapped as wet marsh in 1991. We will also summarize what the composition of wet and dry marshes mapped in 1991 was as of the 2002 and 2013 vegetation classifications.

In order to characterize changes in the composition of marsh communities, we will resample species composition and cover at the locations in Stevens and others (1995) coincident with the annual riparian vegetation monitoring trips (Element 1). Using indicator species defined by Stevens and others (1995), we will assess changes in the composition and relative cover of four different marsh vegetation associations (clonal wet marsh (cattail/reed), nonclonal wet marsh (horseweed/Bermuda-grass), woody phreatophyte (tamarisk/arrowweed), and dry marsh (horsetail/willow). Utilizing environmental niche models developed from the retrospective vegetation analysis (previous work plan), we will model responses of individual species, marsh associations, and total marsh vegetation to alternative flow scenarios. These environmental niche models will define the breadth of river stage conditions that are viable for individual species.

Deliverables: Peer-reviewed journal manuscript that describes marsh community changes since the 1992 ROD and Stevens and others (1995).

Project Element C.(ii). Systemwide decadal-scale vegetation change monitoring

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The limited time depth of currently available vegetation monitoring data limits our ability to interpret vegetation changes in the CRe over decadal temporal scales. The replication and analysis of historical photographs provides a very powerful, cost-efficient, and "user-friendly" means of extending the currently available monitoring record farther back in time. High-quality replications of historical images have been successfully and effectively used by previous researchers to document landscape changes throughout the world (Webb and others, 2010) including desert and riparian vegetation in the Grand Canyon river corridor (Turner and Karpiscak, 1980; Webb, 1996) and in other riparian corridors throughout the American Southwest (e.g., Turner and others, 2003; Webb and others, 2007). More recently, this technique has been used to document significant increases in woody riparian vegetation and other significant riparian vegetation changes occurring within Grand Canyon between the early 1990s and 2010s (Webb and others, 2011). This project element will extend the currently available record of vegetation change in the Colorado river corridor between RM -15.5 and 240 through acquiring replications of photographs taken during several past expeditions on the Colorado River (e.g., 1923 USGS expedition, 1940 Norm Nevills' expedition, 1973 Weeden survey.)

Through collecting high-resolution and precisely replicated historical images, we will not only be able to document long-term changes throughout the riparian zone, but we will simultaneously be creating a baseline visual record at the start of the 20-year LTEMP period that documents the current condition of riparian vegetation throughout the river corridor. These images can be matched at the conclusion of the LTEMP period to document how conditions changed over the course of this 20-year-long experimental plan. A secondary benefit of acquiring these ground-level photographs will be to serve as an independent means of ground-truthing and illustrating vegetation conditions in the riparian zone in support of the ground-based monitoring and remotely sensed analyses being proposed under elements 1 and 2 of this project. Specifically, element C.5 aims to:

1) Precisely replicate historical images taken during past river expeditions using modern, high resolution digital technologies and to systematically analyze pair sets of images for changes in riparian species distribution, growth and abundance.
2) Develop a system-wide visual record of current riparian vegetation and campsite conditions that can serve as a baseline record for future photographic comparisons at the end of LTEMP period.
3) Provide an adjunct source of site-specific, ground-based information on riparian vegetation that is readily accessible to non-scientists and can support and supplement other kinds of monitoring data being collected under elements 1, 2, and 3.

This project element will build upon historical photo replication efforts initiated through a pilot study in the FY2015-17 work plan, but this element will be specifically targeted at developing a system-wide visual record of riparian conditions at the start of the LTEMP period. This record can be used to monitor changes retroactively as well as into the future. We anticipate acquiring hundreds of replicated images over the duration of this three year work effort. Each paired set of images will be systematically analyzed for presence and abundance of common riparian species. The images will be annotated in the field to document where vegetation has persisted or changed through time, as well as any obvious changes in geomorphic setting and substrates that may affect species composition. The photographic replication work will be conducted in association with other vegetation monitoring work and/or with other scientific research, administrative or tribal monitoring trips whose schedules are compatible with the logistical requirements of this monitoring effort. All photographs and associated documentation will be digitized and archived with the USGS Southwest Repeat Photography Collection housed at the USGS Campus in Flagstaff, Arizona. These data will be made available online for use by other researchers in the future.

Deliverables: 60-80 replications of historical photos between RM -15 to 240 will be collected each year, with analyses of vegetation change between paired sets. Peer-reviewed journal article in FY2020 will describes conditions at start of LTEMP and changes observed since 1923.

Project D. Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites

1. Investigators

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, and others (see each project element below for specific lead investigator and collaborators)

2. Project Summary

Glen Canyon Dam has reduced downstream sediment supply to the Colorado River by about 95% in the reach upstream of the Little Colorado River confluence and by about 85% below the confluence (Topping and others, 2000). Operation of the dam for hydropower generation has additionally altered the flow regime of the river in Grand Canyon, largely eliminating pre-dam low flows (i.e., below 5,000 ft^3/s) that historically exposed large areas of bare sand (U.S. Department of the Interior, 2016a; Kasprak and others, 2017). At the same time, the combination of elevated low flows coupled with the elimination of large, regularly-occurring spring floods in excess of 70,000 ft^3/s has led to widespread riparian vegetation encroachment along the river, further reducing the extent of bare sand (U.S. Department of the Interior, 2016a, Sankey and others, 2015).

The changes in the flow regime, the reductions in river sediment supply and bare sand, and the proliferation of riparian vegetation have affected the condition and physical integrity of archaeological sites and resulted in erosion of the upland landscape surface by reducing the transfer (termed "connectivity") of sediment from the active river channel (e.g., sandbars) to terraces and other river sediment deposits in the adjoining landscape (U.S. Department of Interior, 2016a; Draut, 2012; East and others, 2016). Many archaeological sites and other evidence of past human activity are now subject to accelerated degradation due to reductions in sediment connectivity under current dam operations and riparian vegetation expansion tied to regulated flow regimes (U.S. Department of the Interior, 2016a; East and others, 2016).

The LTEMP EIS predicts that conditions for achieving the goal for cultural resources, termed "preservation in place", will be enhanced as a result of implementing the selected alternative. HFEs are one component of the selected alternative that will be used to resupply sediment to sandbars in Marble and Grand Canyons, which in conjunction with targeted vegetation removal, is expected to resupply more sediment via wind transport to archaeological sites, depending on site-specific riparian vegetation and geomorphic conditions (Sankey and others, 2017).
At the same time, HFEs can also directly erode some river sediment deposits containing cultural

resources, particularly large terraces in the Glen Canyon reach (U.S. Department of Interior, 2016a).

This project quantifies the geomorphic effects of ongoing and experimental dam operations, as well as the geomorphic effects of riparian vegetation expansion and management, focusing on effects to the supply of sediment to cultural sites and terraces. The ongoing and experimental dam operations and vegetation management of interest are those that will be undertaken under the LTEMP ROD (U.S. Department of the Interior, 2016b) during the next 20 years. The data and analyses from this project will allow the GCDAMP to objectively evaluate whether and how these non-flow and flow actions affect cultural resources, vegetation, and sediment dynamics, and how they ultimately affect the long term preservation of cultural resources and other culturally-valued and ecologically important landscape elements located within the river corridor downstream of GCD.

3. Hypotheses and Science Questions

The proposed work in this project is divided into two project elements (though see also two additional elements that were proposed but not included in the final work plan). These two elements are individually and collectively addressing a suite of science questions, the answers to which will help to inform future management of dam-affected cultural resources in the CRe and ensure that future flow and non-flow actions that are intended to maintain or improve resource condition are based on solid foundation of quantitative scientific information. The main scientific questions that the project elements are designed to answer are:

- What have we learned from the past three decades of research and monitoring about the factors and processes affecting cultural resource site integrity in the CRe, and how can we build on this learning to improve the protection and preservation of cultural resources going forward?
- How do dam-controlled flows directly affect the physical condition of archaeological sites in the downstream river corridor?
- Are individual features or cultural deposits within archaeological sites being affected by surface changes, and if so, at what rate are these changes occurring and what are the relative contributions of dam related effects vs. non-dam related impacts, such as natural processes or visitor use?
- How do differences in the potential for sites to receive sand from the active river channel and controlled-flood deposits affect site condition over time?
- Will the increase in frequency of controlled floods associated with the HFE protocol that began in 2012 (and allows for floods to be implemented annually as long as environmental conditions support their use) increase the resupply of river sand to archaeological sites during the next 20 years under the LTEMP ROD?

- Does removal of woody riparian vegetation at select locations significantly increase deposition of sand at individual source-bordering dunefields and thus promote burial of archaeological sites there?

4. Background

More than two decades of research and monitoring in the CRe have demonstrated that throughout Grand Canyon, numerous terraces and the cultural resources contained therein, are subject to degradation from erosion processes and visitor impacts (U.S. Department of the Interior, 2016a). Many of these landforms are located above the elevations inundated by the contemporary river channel, yet research and monitoring have demonstrated that the effects of dam operations have nonetheless accelerated and exacerbated rates of erosion affecting these landforms (U.S. Department of the Interior, 2016a; East and others, 2016). Research has shown that the landforms containing many cultural resource sites have become disconnected (i.e., no longer receive sediment) from the active river channel downstream of the dam due to the combination of reduced sediment supply in the river, riparian vegetation encroachment, and alterations in flow, which historically supplied sediment (e.g., during floods) but also exposed that sediment for transport (e.g., by wind during low flows; East and others, 2016; Kasprak and others, 2017).

Terraces are a substantial component of sediment resources in the ecosystem. They additionally contain widespread evidence of past human activity (e.g., archaeological sites; U.S. Department of the Interior, 2016a). Thus, the ongoing loss of these sediment deposits is contributing to the loss of all sediment-dependent resources in the CRe, including cultural sites (U.S. Department of the Interior, 2016a; Collins and others, 2016). In some places, for example at the large terraces in the Glen Canyon reach of the Colorado River, sediment transfer between the active river channel and upland areas occurs primarily through fluvial and mass failure processes. In these areas HFEs have resulted in the erosion of terraces, mainly from the change in pore pressure gradient after flood water recession exposes saturated terrace banks, which then shed material into the river channel (U.S. Department of the Interior, 2016a; Grams and others, 2007). In other areas, sediment connectivity results from aeolian transport of sand from sandbars to dunefields (U.S. Department of the Interior, 2016a; East and others, 2016; Draut, 2012). In both situations, the deposition or erosion of sediment in the terraces can have direct impacts on buried or exposed archaeological sites situated on these surfaces, and can also have indirect impacts such as offsetting rates of erosion from natural processes in the surrounding landscape (U.S. Department of the Interior, 2016a; Collins and others, 2016; Sankey and others, 2014). These impacts are in turn interpreted by NPS and tribal resource managers as being either beneficial or deleterious to the cultural resources in question.

The LTEMP (U.S. Department of Interior, 2016a) relied on a series of conceptual and numerical models to evaluate the likely responses of resources to a suite of proposed alternatives for operating GCD over the next 20 years. The models incorporated past scientific learning and produced generalized predictions about how resource conditions would potentially change under each alternative. The model-based analyses predicted that Alternative D, the alternative ultimately selected for implementation in the LTEMP ROD (U.S. Department of the Interior, 2016b), would result in modest benefits for cultural resources by improving sediment conditions that help to stabilize and preserve archaeological sites in situ, while also benefiting natural processes, campsites, riparian vegetation, hydropower, endangered fish, and other resources valued by society.

Over the past decade, GCMRC scientists have developed and refined methods for tracking trends and quantifying rates, amounts, and sources of geomorphic change affecting cultural resources in the CRe (Kasprak and others, 2017; Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016). These methods are perfectly suited to evaluating whether the predictions of resource improvement in the LTEMP occur over the next 20 years (U.S. Department of Interior, 2016a,b). Specifically, the methods can be used to evaluate whether changes in operations improve sediment supply to archaeological sites and the associated terraces and landscapes in which these sites are embedded, and whether such changes in turn result in a reduction of erosion rates and improved preservation of the physical attributes that are necessary to maintain site integrity under the National Historical Preservation Act.

The LTEMP EIS (U.S. Department of the Interior, 2016a) identifies river terraces, specifically in the Glen Canyon National Recreation Area (GLCA) reach, as being vulnerable to erosion and degradation from HFEs which are otherwise intended to distribute sediment throughout the Colorado River downstream of the Paria River (see also Grams and others, 2007). NPS and tribal resource managers have identified a need for quantifying the effects of dam operations on the erosion of terraces and other river sediment deposits in Glen, Marble, and Grand Canyons by determining erosion rates during the approximately two decades since the implementation of the previous ROD (U.S. Department of Interior, 1996) with river flow regime of episodic controlled floods and restricted hydropeaking (U.S. Department of the Interior, 2016b).

The current LTEMP ROD (U.S. Department of the Interior, 2016b, subsection 6.4.) also identifies vegetation management as a non-flow action that will be used to assist with cultural site protection. Accordingly, the NPS wants to work with tribal partners and GCMRC to remove woody riparian vegetation at individual sites in order to increase the amount of river sand that is transported by wind and deposited on adjacent sand dunes, terraces, and archaeological sites. GCMRC's ongoing program for monitoring the effects of dam operations on the geomorphic condition of archaeological sites, which was implemented in Project 4 (of the FY2015-17 work plan), is well-suited for identifying sites for pilot vegetation removal projects and for quantifying the effectiveness of the treatments.

5. Proposed Work

5.1. Project Elements

Project Element D.1. Geomorphic effects of dam operations and vegetation management

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Helen Fairley, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Jen Dierker, National Park Service, Grand Canyon National Park
Ellen Brennan, National Park Service, Grand Canyon National Park

This project element will use the plan for monitoring the geomorphic condition of archaeological sites implemented during Project 4 (FY2015-17 TWP) to quantify changes in the physical condition of archaeological sites, surrounding landscapes, and site-scale sediment connectivity as a function of; (i) dam operations, (ii) natural processes, and (iii) vegetation management conducted by NPS and Tribes under the LTEMP ROD (U.S. Department of the Interior, 2016b). Science questions that the monitoring plan is designed to answer via collection and analysis of long-term monitoring data are:

- How do dam-controlled flows directly affect the physical condition of archaeological sites in the downstream river corridor?
- Are individual features or cultural deposits within archaeological sites being affected by surface changes, and if so, at what rate are these changes occurring and what are the relative contributions of dam related effects vs. non-dam related impacts, such as natural processes?
- How do differences in the potential for sites to receive windblown sand from the active river channel and controlled-flood deposits affect site condition over time?

Monitoring in this project element is performed at the scale of individual archaeological sites, the immediate surrounding landscape, and concentrations of archaeological features within sites. Monitoring will specifically focus on quantifying changes in physical condition, including effects to site-specific attributes that are important to maintaining archaeological site integrity, using geomorphic change detection (GCD) methods based on high-resolution topographic survey data (e.g., LiDAR, structure-from-motion, total station; Kasprak and others, 2017; Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016; Wheaton and others, 2013). Geomorphic change detection, which has been extensively used by our group in the past, quantifies the degree of erosion or deposition at archaeological sites and concentrations of archaeological features through time. Importantly, however, geomorphic change detection does not provide information on the processes causing those topographic changes. To this end, we will use a new software utility developed in Project 4 (FY2015-17 work plan) to attribute observed geomorphic changes to individual geomorphic processes (fluvial, alluvial, colluvial, and aeolian) driving change (Figure 1; Kasprak and others, 2017). We then use additional sources of data including river discharge (https://www.gcmrc.gov/discharge_qw_sediment/), modelled inundation extents (Magirl and others, 2008), and meteorology (Caster and others, 2014; Caster and Sankey, 2016) to determine whether changes are driven by or related to dam operations and/or natural processes. One important river-management related question that this monitoring will address is whether the increase in frequency of controlled floods associated with the HFE protocol that began in 2012 (and allows for floods to be implemented annually as long as environmental conditions support their use) will increase the resupply of river sand to archaeological sites during the next 20 years under the LTEMP ROD.

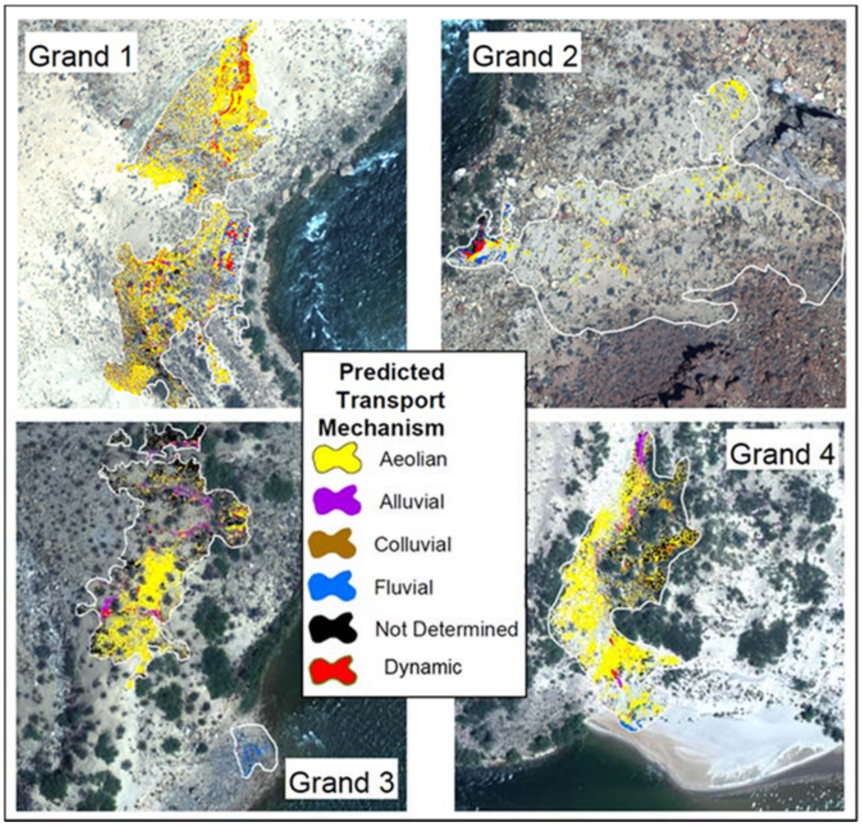

Figure 4. Areas where geomorphic changes occurred during a time period spanning the 2012, 2013, 2014 HFEs at four archaeological sites in Grand Canyon. Changes were determined from analysis of repeat LiDAR surveys, and are mapped by geomorphic process using the automated classification technique developed by Kasprak and others, (2017) during Project 4 of the 2015-17 TWP.

Monitoring will not entail any additional site classification work (e.g., we will not be updating the aeolian classification presented in East and others, 2016). However, the archaeological site classification data collected during Project 4 will be used to draw inferences about the relative roles of dam operations (including experimental flows), natural processes, and vegetation management in driving geomorphic change at sites, and also for selecting treatment and control sites for evaluating the effects of vegetation removal (East and others, 2016). For example, the four archaeological sites shown in Figure 1 are all locations where we know that wind can transport sand from sand bars to the source-bordering dunefields containing the archaeological sites (East and others, 2016). During a time period spanning the 2012, 2013, and 2014 HFEs, the Grand 3 and 4 sites in Figure 1 were resupplied with river sand via aeolian transport whereas the Grand 1 and 2 sites were not (Table 2). Importantly, two of the sites – Grand 2 and 3 – have small but dense barriers of woody riparian vegetation that limits the aeolian transport of sand, and thus are good candidates for experimental vegetation removal pilot projects (Figure 2).

Table 2. Magnitude of aeolian topographic changes at the four Grand Canyon archaeological sites (shown in Figure 1) during the period of the 2012, 2013, and 2014 HFEs.

Site	Net change in aeolian sediment volume (m^3)	Average change in aeolian sediment depth (cm)
Grand 1	- 55.1	- 1.42
Grand 2	- 2.9	- 0.05
Grand 3	+ 2.4	+ 0.09
Grand 4	+ 16.3	+ 0.57

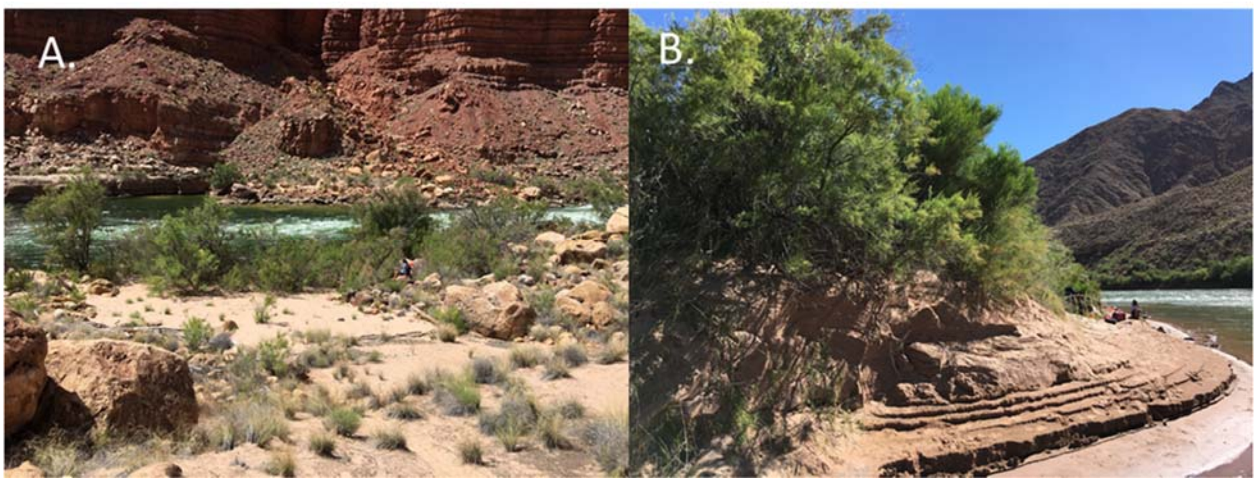

Figure 2. Photos of woody riparian vegetation that forms barriers to aeolian transport at A.) Grand 2 and B.) Grand 3 sites (from Figure 1).

During FY2018 we will assist the NPS and Tribes to select sites, design, and implement experimental vegetation removal treatments to increase sediment connectivity between sandbars and archaeological sites, per the LTEMP ROD (U.S. Department of the Interior, 2016b, subsection 6.4.). We have already identified several locations, including those sites presented in Figures 1 and 2, where previous monitoring provides a clear rationale for conducting experimental vegetation removal. We propose to use our extensive site-scale topographic and land cover data to assist the NPS and Tribes in developing and implementing pilot vegetation removal projects in FY2018, and to then quantitatively evaluate the effects of these treatments in subsequent years using our methods for monitoring the geomorphic condition of archaeological sites. Specific to vegetation management, a hypothesis of this project element is that removal of woody riparian vegetation at select locations can significantly increase deposition of sand at individual source-bordering dunefields and thus promote burial of archaeological sites.

We will meet with NPS and Tribes during the beginning of FY2018 to discuss the pilot vegetation removal projects. This will occur in coordination with meetings planned for scoping the LTEMP vegetation management efforts as a whole. Assuming that we reach consensus to implement pilot project(s) for archaeological sites, we will begin vegetation removal planning support starting in spring of FY2018. Importantly, GCMRC will be providing decision support to help design vegetation management treatments and will be providing science expertise to monitor the outcome of treatments (see project C and element C.4). However, the NPS and/or Tribes as resource managers will conduct on-the-ground implementation of vegetation removal treatments. We intend to collaborate by sharing logistics and personnel – such as during our planned monitoring river trips – to assist the land managers in implementing experiments, conducting on-the-ground work, and collecting initial pre- and post-treatment monitoring data. Coordination in all aspects of the vegetation management work is extremely important because implementation of vegetation removal treatments and evaluation of post-treatment site geomorphic condition should focus on locations where the deposition of sand is perceived by resource managers (i.e., NPS and Tribes) as having the potential to positively impact the preservation of cultural resources and possibly other sediment-dependent resources such as culturally important plants.

Project element D.2. Cultural resources synthesis to inform Historic Preservation Plan
Helen Fairley, USGS GCMRC, in collaboration with PA signatories

Reclamation and other signatories to the new Section 106 Programmatic Agreement for Cultural Resources (PA) have identified the need for a synthesis of past monitoring, research, and mitigation of dam operations' effects and other impacts to cultural resources in the CRe. This synthesis is needed to help inform development of a new Historic Preservation Plan for historic properties in the CRe and to aid future decision-making and management of historic properties affected by dam operations. The synthesis will provide foundational information to address several broad and persistent management-related questions such as:

- Are individual features or cultural deposits within archaeological sites being affected by dam-related surface changes, and if so, at what sites are these changes occurring, at what rate are these changes occurring, and what are the relative contributions of dam related effects vs. non-dam related impacts, such as visitor use?
- What have we learned from the past three decades of research and monitoring about the factors and processes affecting cultural resource site integrity in the CRe, and how can we build on this learning to improve the protection and preservation of cultural resources going forward?

- What have we learned from the past three decades of monitoring about which sites are at greatest risk from dam-related impacts?
- What have we learned from the past three decades of research and data recovery about site formation and degradation processes in the CRe?
- How can we improve monitoring, data recovery, and mitigation methods to more effectively address dam operations effects to archaeological and TCP site condition?

This project will involve reviewing, evaluating and synthesizing past monitoring, research, and mitigation projects and associated scientific data collected over the past three decades (early 1980s through 2017) related to cultural resources in the Colorado River ecosystem (CRe) that have potential to be affected by dam operations. The synthesis will include a management summary table for all identified historic properties within the CRe, including Traditional Cultural Properties, for which publicly accessible information (e.g., tribal reports prepared in the early 1990s and more recent tribal monitoring reports) is available. For each individual property, the table will include a summary of documented impacts to each resource (including impacts from GCDAMP-related activities), previous actions (monitoring, research, and/or mitigation) undertaken at each property, long-term management goals for the property (to the extent that they have been established), and citations for all the extant reports that reference each specific property. In addition, the synthesis will assemble and analyze information from previous data recovery efforts in the CRe to extract information about pre-dam site formation processes, particularly the role of floods and other sediment transport processes in forming site contexts, and how the pre-dam processes compare to site formation and preservation processes occurring under current dam operations.

In developing this synthesis, GCMRC's cultural program manager will work closely with agency personnel, Tribes, and other GCDAMP stakeholders to ensure that all relevant sources of information are included in the synthesis and to identify other specific issues and sub-topics that agency and tribal managers and other GCDAMP stakeholders believe are important to consider. GCMRC's cultural program manager will also consult with the wider archaeological research community to ensure that the resulting synthesis is well-founded, objective, and thorough in its evaluation and synthesis of currently available data.

Once a draft of the initial synthesis has been completed, GCMRC's cultural program manager will initiate a pilot analysis of a subset of the hundreds of photographs that have been assembled over the previous two plus decades of monitoring cultural resources in the CRe, to extract as much information as possible about the processes affecting historic properties in the CRe and to assess their utility for future monitoring purposes. This analysis of the legacy photograph collection was previously recommended by a scientific review panel in 2007 (Kintigh and others, 2007). GCMRC's cultural program manager will collaborate with NPS archaeologists and Tribal colleagues to ensure that this analysis meets the needs and interests of the GCDAMP cultural program, as well as the broader scientific information needs of the GCDAMP. Qualitative and semi-quantitative analysis methods developed in collaboration with Reclamation, NPS and the tribes will be employed. The resulting data and report will provide additional baseline information about the causes and processes affecting cultural resources in the CRe to help inform future decisions and priority-setting.

5.2. Deliverables

Element D.1: Annual vegetation removal treatment and site geomorphic condition monitoring reports to NPS, Tribes (and all stakeholders). A journal publication that describes the results of the initial experimental treatments approximately two years into post-treatment monitoring. Published datasets.

Element D.2: A peer-reviewed report synthesizing past monitoring, research and mitigation work performed at historic properties within the CRe and a second report synthesizing the changes and impacts that have been recorded in 20 plus years of photographs taken at cultural resource sites in the CRe. A draft of the synthesis report will be prepared during the first six months of FY2018, and the report will be finalized two months following receipt of all comments and feedback from agency and tribal reviewers. The analysis of legacy monitoring photographs will commence in FY19, following completion of the synthesis report, and a report on the photographic analysis will be completed in FY20.

6. References

Caster, J.J., Dealy, T.P., Andrews, T., Fairley, H., East, A., and Sankey, J.B., 2014, Meteorological data for selected sites along the Colorado River Corridor, Arizona, 2011-13: U.S. Geological Survey USGS Open-File Report 2014-1247, 56 p., http://dx.doi.org/10.3133/ofr20141247.

Caster, J.J., and Sankey, J.B., 2016, Variability in rainfall at monitoring stations and derivation of a long-term rainfall intensity record in the Grand Canyon Region, Arizona, USA: U.S. Geological Survey Scientific Investigations Report 2016-5012, 38 p., https://pubs.er.usgs.gov/publication/sir20165012

Collins, B.D., Bedford, D.R., Corbett, S.C., Cronkite-Ratcliff, C., and Fairley, H., 2016, Relations between rainfall-runoff-induced erosion and aeolian deposition at archaeological sites in a semi-arid dam-controlled river corridor: Earth Surface Processes and Landforms, v. 41, no. 7, p. 899-917, http://dx.doi.org/10.1002/esp.3874.

Collins, B.D., Corbett, S.C., Sankey, J.B., and Fairley, H.C., 2014, High-resolution topography and geomorphology of select archeological sites in Glen Canyon National Recreation Area, Arizona: U.S. Geological Survey Scientific Investigations Report 2014-5126, 31 p., http://dx.doi.org/10.3133/sir20145126.

Collins, B.D., Brown, K.M., and Fairley, H.C., 2008, Evaluation of terrestrial LIDAR for monitoring geomorphic change at archeological sites in Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008-1384, 60 p., http://pubs.usgs.gov/of/2008/1384/.

Collins, B.D., Minasian, D., and Kayen, R., 2009, Topographic change detection at select archaeological sites in Grand Canyon National Park, Arizona, 2006-2007: U.S. Geological Survey Scientific Investigations Report 2009-5116, 97 p., http://pubs.usgs.gov/sir/2009/5116/.

Collins, B.D., Corbett, S.C., Fairley, H.C., Minasian, D., Kayen, R., Dealy, T.P., and Bedford, D.R., 2012, Topographic change detection at select archeological sites in Grand Canyon National Park, Arizona, 2007–2010: U.S. Geological Survey Scientific Investigations Report 2012-5133, 77 p., http://pubs.usgs.gov/sir/2012/5133/.

Draut, A.E., 2012, Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA: Journal of Geophysical Research—Earth Surface, v. 117, no. F2, http://dx.doi.org/10.1029/2011JF002329.

East, A.E., Collins, B.D., Sankey, J.B., Corbett, S.C., Fairley, H.C., and Caster, J.J., 2016, Conditions and processes affecting sand resources at archeological sites in the Colorado River corridor below Glen Canyon Dam, Arizona: U.S. Geological Survey Professional Paper 1825, 104 p., http://dx.doi.org/10.3133/pp1825.

Grams, P.E., Schmidt, J.C., and Topping, D.J., 2007, The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000: Geological Society of America Bulletin, v. 119, no. 5-6, p. 556-575, http://dx.doi.org/10.1130/B25969.1.

Kasprak, A., Caster, J.J., and Bangen, S.G., 2017, Geomorphic process from topographic form—Automating the interpretation of repeat survey data in river valleys: Earth Surface Processes and Landforms, early view, available at http://dx.doi.org/10.1002/esp.4143.

Kasprak, A., Buscombe, D., Caster, J, East, A, Grams, P., Fairley, H., Sankey, J.B., 2017. The Individual and Additive Effects of Hydrologic Alteration and Vegetation Encroachment on Sediment Connectivity in Grand Canyon. Presentation to the Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 24th 2017, Phoenix, AZ. https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR6_Kasprak.pdf

Kintigh, K., Altschul, J., Lipe, W., and Urquhart, N.S., 2007, Legacy monitoring data review panel report to the Grand Canyon Monitoring and Research Center: Glen Canyon Dam Adaptive Management Program Technical Work Group, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 41 p., http://www.usbr.gov/uc/rm/amp/twg/mtgs/07dec04/Attach_10.pdf.

Magirl, C.S., Breedlove, M.J., Webb, R.H., and Griffiths, P.G., 2008, Modeling water-surface elevations and virtual shorelines for the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Scientific Investigations Report 2008-5075, 32 p., http://pubs.usgs.gov/sir/2008/5075.

Sankey, J.B., and 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, v. 220, p. 68-80, http://dx.doi.org/10.1016/j.geomorph.2014.05.028.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, http://dx.doi.org/10.1002/2015JG002991.

Sankey, J.B., Kasprak, A., Caster, J., Fairley, H.C., East, A.E., 2017. Fluvial-aeolian sediment connectivity during the current HFE protocol—Effects for dunefields and archaeological sites. Presentation to the Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 24th 2017, Phoenix, AZ. https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR5_Sankey.pdf

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport—1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515-542, http://dx.doi.org/10.1029/1999WR900285.

U.S. Department of the Interior, 1996, Record of Decision—Operation of Glen Canyon Dam Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Glen Canyon Dam Adaptive Management Program, 15 p., http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf.

U.S. Department of Interior, 2016a, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

U.S. Department of Interior, 2016b, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Wheaton, J.M., Brasington, J., Darby, S.E., Kasprak, A., Sear, D., and Vericat, D., 2013, Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river: Journal of Geophysical Research—Earth Surface, v. 118, no. 2, p. 759-779, http://dx.doi.org/10.1002/jgrf.20060.

7. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$152,693	$4,750	$11,075	$21,958			$29,632	$220,108
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$33,668	$2,500					$5,627	$41,795
	Total D	**$186,361**	**$7,250**	**$11,075**	**$21,958**	**$0**	**$0**	**$35,259**	**$261,903**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$157,669	$4,750	$11,850	$24,044			$51,561	$249,874
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$34,811						$9,051	$43,862
	Total D	**$192,481**	**$4,750**	**$11,850**	**$24,044**	**$0**	**$0**	**$60,612**	**$293,737**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$163,616	$4,750	$7,100	$24,974			$52,114	$252,554
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$35,993						$9,358	$45,351
	Total D	**$199,609**	**$4,750**	**$7,100**	**$24,974**	**$0**	**$0**	**$61,472**	**$297,905**

8. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element D.(i). Contemporary changes at terraces and other river sediment deposits

Joel Sankey, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Brian Harmon, National Park Service, Grand Canyon National Park
Paul Grams, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Helen Fairley, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element will determine recent erosion rates of terraces and other pre-dam river sediment deposits from dam operations in Glen Canyon and also compare the rates to locations downstream in Marble and Grand Canyons. In the GLCA this will involve collaboration with GLCA archaeology staff who have asked GCMRC to assist with:

1) Identifying terrace deposits that are at risk from flow-related erosion,
2) Quantifying how terraces are changing due to bank and gully erosion, and
3) Completing site-specific geomorphic change detection before and after future HFEs.

The first component of the collaboration with GLCA will be to map the existing deposits and update the assessment of dam-related geomorphic changes in Glen Canyon published by Grams and others (2007) which originally quantified the rate and pattern of bed incision and bank adjustment between 1956 and 2000. We will employ post-2000 remote sensing imagery, topography, bathymetry, and flow (inundation) modeling, as well as additional field-based terrace and vegetation mapping in order to update the assessment and then deliver the datasets to GLCA archaeology staff. This will result in a collaborative evaluation of contemporary (post-2000) changes to Glen Canyon's terraces, shorelines, and riparian vegetation that are relevant for the NPS goals of preserving cultural resources and archaeological sites. We will also estimate rates and patterns of geomorphic changes on terraces relative to dam operations in Glen Canyon and then compare these to similarly estimated rates and patterns in reaches with large river terraces in downstream Marble and Grand Canyons. Our methods for the comparison will be to complete geomorphic change detection of 1-m resolution DEMs (Digital Elevation Model) acquired from aerial overflights in 2002, 2009, and 2013. We will then implement the new software utility published by Kasprak and others (2017), which attributes observed geomorphic changes to individual geomorphic processes driving change (Figure 1). We will improve the software to specifically include the process of terrace bank failure in addition to other fluvial, alluvial, colluvial, and aeolian geomorphic processes. The estimates and comparisons will be directly useful to NPS and tribal resource managers who want to know the rates and patterns of erosion on large terraces in the CRe during the approximately two decades since the implementation of the previous ROD (U.S. Department of Interior, 1996) through the next 20 years of the current LTEMP ROD (U.S. Department of the Interior, 2016b). This work will be completed in FY2018 and 2019.

The second component of the collaboration with GLCA will be to use survey and remote sensing techniques to quantify geomorphic changes associated with future HFEs. GLCA archaeology staff will identify site-specific monitoring locations and GCMRC will assist but also train the GLCA archaeology staff to collect imagery and topographic data using ground and UAS-based photogrammetry (structure-from-motion) as well as LiDAR (Figure 3). GCMRC will process the data and perform geomorphic change detection and will then deliver the derivative datasets to the GLCA staff. GLCA and GCMRC will collaborate to interpret, summarize, and report on the monitoring results. Data collection and training of GLCA staff will be conducted in FY2018 and FY2019 but not during FY2020 for this element. The project element and GCMRC budget will be scaled back in FY2020 to focus on transferring capacity for such HFE-related monitoring in the future to GLCA.

In addition to HFEs, boat wakes can also potentially erode the banks of river terraces in Glen Canyon. Thus, we will conduct a pilot investigation to compare our measurements of erosion from HFEs at several locations within Glen Canyon to estimates of erosion from boat wakes to determine the potential contribution of boat traffic to overall terrace erosion. We will first use video observations to estimate swash zone associated with individual boat passes. We will also attempt to estimate how those parameters vary with several different classes of boats. We will bracket the video observations with detailed topographic surveys and use change detection to estimate the magnitude and spatial distribution of erosion attributed to the wakes during that timeframe. When possible, we will conduct these observations during steady flow experiments (e.g., weekend bug flows) so as to minimize the effects of fluctuations in river discharge. We will extrapolate estimates of erosion from the observations to longer time periods using observations of boat traffic in the Glen Canyon reach of the river.

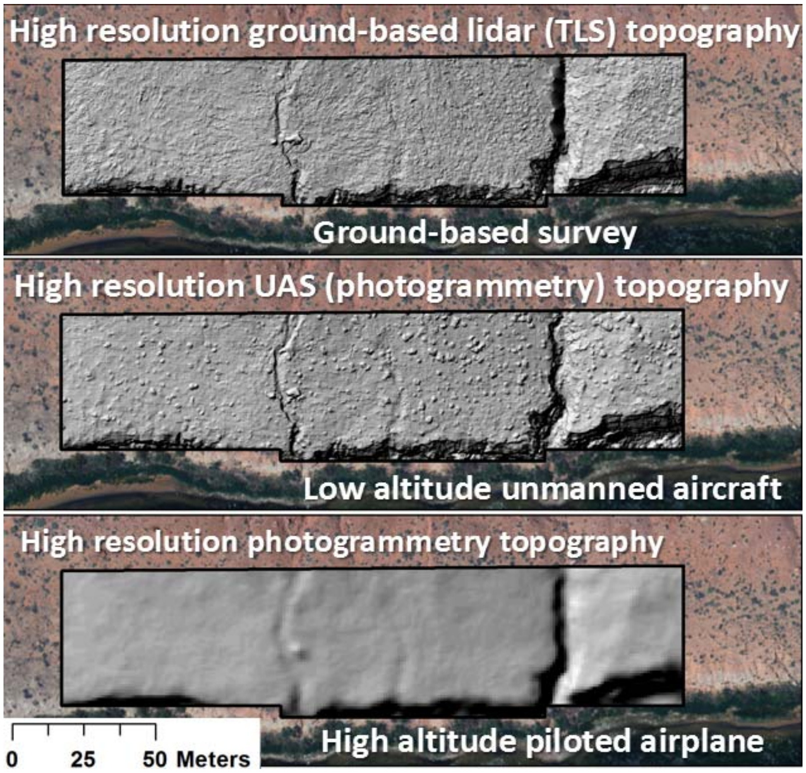

Figure 3. Examples of digital elevation models (DEMs) for a terrace in Glen Canyon from high resolution topographic surveys conducted with ground-based LiDAR (top), Unmanned Aerial Systems (UAS) photogrammetry (middle), and airplane overflight photogrammetry. Time series of DEMs such as these are used for estimating rates and patterns of erosion on terraces with geomorphic change detection and the software utility of Kasprak and others (2017). Photogrammetry from UAS (middle) or ground survey (example not shown) are particularly efficient and affordable methods for future HFE-related monitoring by GLCA archaeology staff. TLS is an acronym for Terrestrial Laser Scanner and is synonymous with ground-based LiDAR.

Project Element D.(ii). Effects of dam operations and vegetation on the areal extent of bare sand
Joel Sankey, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This element will synthesize data from Projects B, C, and D to quantify the influence of GCD discharge and vegetation encroachment on altering the areal extent of bare sand available for fluvial and aeolian transport from GCD to Bright Angel Creek (RM -15 to RM 88). Note that while Elements D.1 and D.2 primarily provide information on cultural resource condition and geomorphic change at individual archaeological sites and the immediately adjacent landscape, this element will inform our understanding of sediment resources continuously at the river corridor scale. This research will be completed over a two-year period beginning in FY2018 and concluding in FY2019.

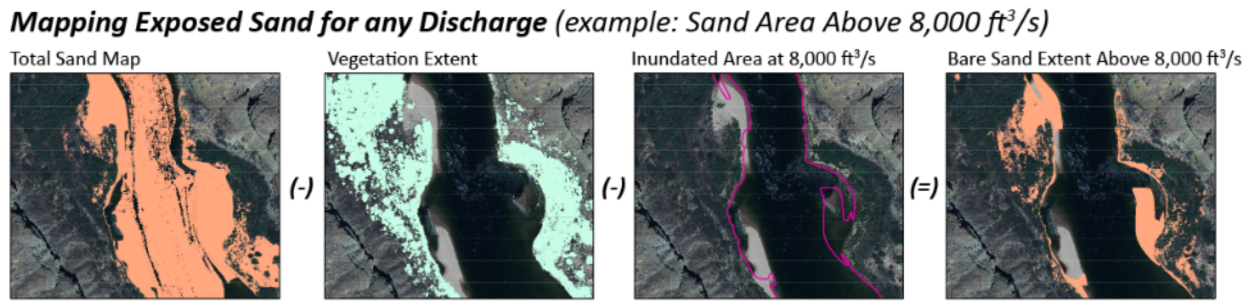

Figure 4. Methodology for computing areal extent of bare sand for any discharge. A map of all bare sand is produced by combining data from channel mapping and air photo mapping. From this, vegetated areas are removed, as are any inundated areas where sand would be underwater for a given flow. The result is a map depicting the total area of bare sand for a reach and discharge of interest.

For a 16-mile study reach from RM 46 to RM 62, where such data on the extent of sand and vegetation are available, Kasprak and others (2017) found that hydrologic alteration following the closure of GCD reduced the areal extent of bare sand by 14%, vegetation encroachment over the same period reduced sand extent by 20%, and the additive effect of altered hydrology and vegetation resulted in a 27% reduction in bare sand area between the pre- and post-dam periods (Figure 2). Kasprak and others (2017) also found that at present, roughly 50% of all non-vegetated sand in this reach is located above the contemporary low-flow stage, with the remaining 50% being inundated nearly continuously, meaning that any future changes in flow regime or vegetation coverage will have large implications for the amount of bare sand found throughout the river corridor. Over the next 20 years (i.e., during the LTEMP), the extent of bare sand is projected to be further reduced by an additional 14% from its current extent. Importantly, however, the individual and additive effects of hydrologic alteration and vegetation encroachment on the areal extent of bare sand, and their subsequent role in affecting the maintenance of river-derived sand deposits, including sandbars and dunefields, remain unknown outside of this 16-mile pilot study reach, which may or may not be representative of conditions throughout Grand Canyon.

From work completed during the FY2015-2017 work plan, continuous maps of bare sand and vegetation extent will be available from GCD to Bright Angel Creek by the end of FY2017. Project Element D.3 will leverage these data to extend the 16-mile proof-of-concept work completed by Kasprak and others (2017) to quantify the role of hydrologic alteration and vegetation encroachment on bare sand extent continuously along this entire 103-mile reach. The results of this analysis will evaluate the degree to which bare sand alteration results from GCD operations and how this relationship may vary longitudinally along the CRe. Because this method can also be used to forecast the implications of future flow and vegetation scenarios on bare sand extent, the work will provide a corridor-scale modeling framework for quantifying the effects of proposed flow regimes and vegetation removal efforts on the extent of sand available for building sandbars, maintaining existing campsites, and promoting fluvial-hillslope sediment exchange for the preservation of cultural resources.

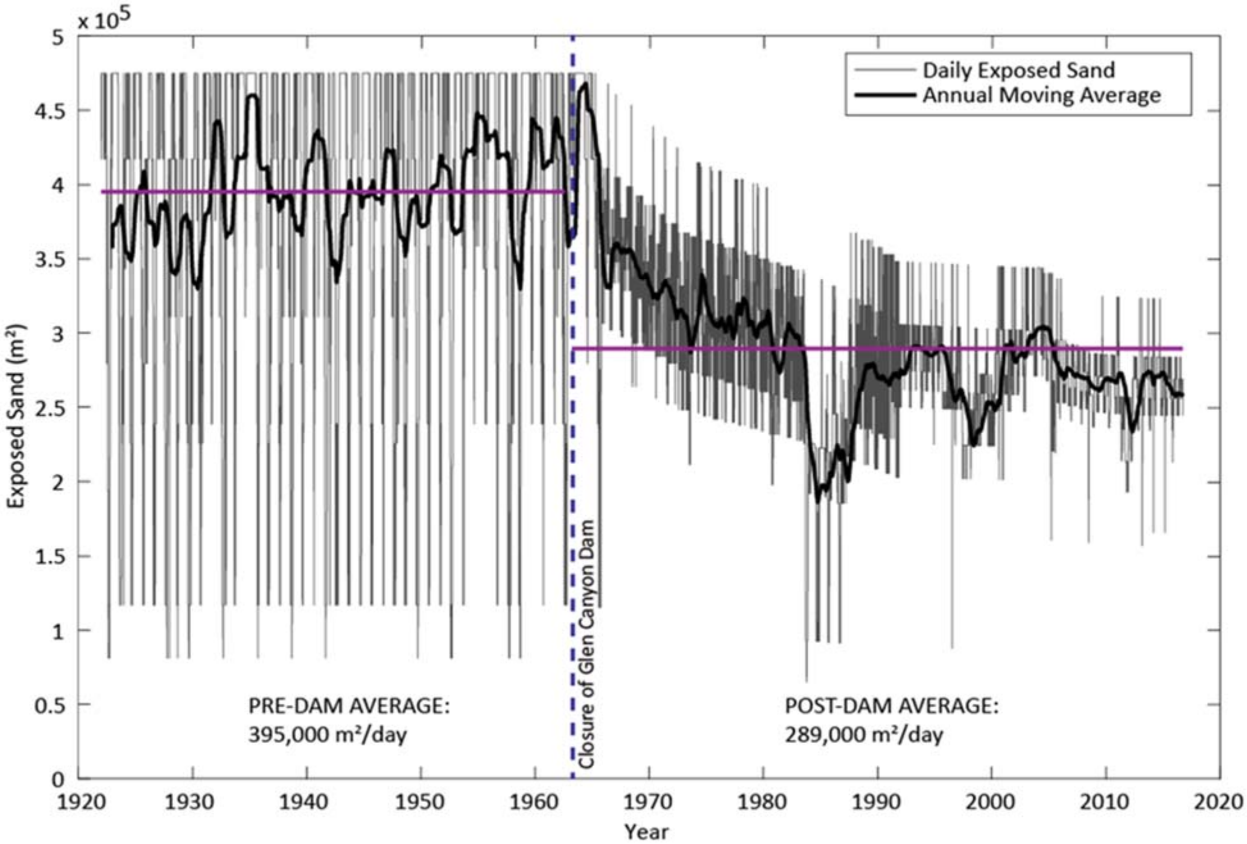

Figure 5. The areal extent of exposed sand each day as a function of hydrologic alteration and vegetation encroachment for the period 1922-2016 for a 16 mile pilot study reach (RM 46-62). Day-to-day variability in exposed sand is due to changing Colorado River flows; higher flows reduce exposed sand area and low flows increase area. The decreasing trend in exposed sand area in the post-dam period is due to steady vegetation encroachment. Purple lines show averages for pre- and post-dam periods and indicate a 27% reduction in exposed sand area between the two periods.

Project E. Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future

1. Investigators

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2. Project Summary

Ecosystem temperature and nutrient dynamics can influence both species composition and metabolic rates across many different types of ecosystems (Allen and others, 2005; Brown and others, 2004; Elser and others, 2003; Elser and others, 1996; Yvon-Durocher and others, 2012). Given the importance of nutrients and temperature as drivers of the aquatic ecosystem, it is important to understand their spatio-temporal patterns both because they may be altered by management actions considered in the LTEMP, and because they may provide essential context for interpreting responses to flow experiments. Given the potential importance of nutrients and temperature in driving CRe dynamics, we propose monitoring, research and modeling to: 1) identify processes that drive spatial and temporal variation in nutrients and temperature within the CRe, and 2) establish quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels. Parallel work in Lake Powell that aims to identify the controls on nutrient concentrations in the GCD outflow is planned with external funding from Bureau of Reclamation (see Appendix 1).

Both temperature and nutrients change in response to various processes. A dense network of stream gaging stations in Grand Canyon provides information on temperature at fine temporal resolutions (Project A) and a temperature model exists to predict downriver temperature (Wright and others, 2008). This model was used to predict responses of downriver native fish populations and warm water non-native fish species to management alternatives in the LTEMP. Although the Wright and others (2008) temperature model was a valuable tool for EIS modeling efforts, it has important limitations. For example, Wright and others (2008) clearly acknowledge that their model overestimates temperatures in downstream reaches during fall low flow months by as much as 2 °C, however, this assumption does not appear to have been acknowledged in LTEMP modeling of downstream temperatures. We are currently modifying Wright's model and propose to finish this work in FY2018. These modifications are expected to improve downriver predictions.

In contrast to our detailed understanding of temperature, we lack even a basic understanding of gross patterns in nutrient concentrations and their variation over time and along the river. SRP, the most bioavailable phosphorus, is likely to be especially important given the high N:P in the CRe, but our understanding of patterns in soluble reactive phosphorus (SRP) availability is especially lacking. While continuous nutrient monitoring at Lees Ferry shows a strong correspondence between nutrient availability in the reservoir outflow and in the Lees Ferry reach (Vernieu, 2009), there are very few measurements of nutrients downstream of the Paria River inflow, with no measurements of SRP routinely made. While the dam releases contribute substantially more discharge than all tributary inputs combined, tributaries like the Paria River and LCR are the major sources of sediment and labile organic matter inputs to the Colorado River and can drive riverine suspended sediment dynamics independent of total river discharge (Topping and others, 2007; Ulseth, 2012). In the Paria River, total phosphorus concentrations are 1-2 orders of magnitude higher than in the mainstem Colorado (Lawson, 2007; Deemer unpublished data). While total phosphorus and SRP are both relatively low during baseflow in the LCR (Deemer, unpublished data; Moody and Muehlbauer, unpublished data), we expect that storm events may flush significant amounts of P into the Colorado before this P has time to be sequestered via abiotic reactions (as is highly likely to be occuring during baseflow). More generally, nutrient loads are likely to vary, at least in part, with suspended sediment loads such that storms may be important to overall budgets in the Paria River as well.

Indirect evidence suggests that reservoir inputs may dominate nutrient concentrations in the upper parts of the CRe, but other factors may become more important downriver. For example, as nutrient concentrations in Lake Powell declined during 2014, Colorado River invertebrate and fish populations between GCD and Lees Ferry and near the LCR confluence declined dramatically. However, in more downriver portions of the CRe, the catch of humpback chub, especially juvenile life stages, was higher in 2014 than in prior years. This suggests either that nutrient limitation is currently not a controlling factor in the lower half of the CRe (see hypotheses H5, H6, and H8 in Project G), or that there are unaccounted sources of nutrients in the lower CRe. These unaccounted sources of nutrients in the lower CRe could consist of tributary inputs, release of geologically bound P under different environmental conditions, or elevated mineralization with higher temperature and/or organic matter inputs (see hypothesis H7 in Project G).

To address these critical management uncertainties, we propose a multi-pronged approach that aims to better understand processes affecting temperature and nutrient availability in the CRe, and to further investigate links between these drivers and Colorado River food webs. We have used the available literature and data to generate a suite of 11 hypotheses which are outlined below. While there are many other hypotheses one could generate to describe patterns in nutrients and temperature and their effects on higher trophic levels, we have done our best to select what we believe are the most probable, management-relevant, and feasible-to-test hypotheses with the intention that we can build on this information in future work plans.

3. Hypotheses and Science Questions

1) A model based on exponential warming has lower bias in predictions of water temperature than the Wright model.
2) Primary producers remove SRP as water moves longitudinally with greatest losses in the most productive reaches during the day, when turbidity is low.
3) The LCR is the most important tributary source of SRP when flooding, but at baseflow LCR inputs drive declines in mainstem SRP concentrations by increasing co-precipitation of phosphorous with bicarbonate.
4) The Paria River also contributes significantly to the phosphorous budget of the mainstem Colorado River.
5) Run-off after forest fires provides significant inputs of nutrients, including phosphorous, to the CRe.
6) Dam operations play an important role in spatio-temporal patterns of phosphorous. Specifically:
    a. Portions of the river bed that dry during months of lower maximum flows contribute SRP to the river when they are re-inundated during months of higher maximum flows.
    b. Varial zones experiencing significant tamarisk defoliation via tamarisk beetles contribute to higher SRP release upon re-inundation.
7) The impacts of changes in temperature on the aquatic ecosystem in the CRe will depend crucially on the state of the aquatic food base.
8) Nutrients, in particular SRP, are important drivers of overall ecosystem productivity.
9) Competing, but not mutually exclusive, flow-based hypotheses include:
    a. Spring HFEs stimulate the aquatic food base and rainbow trout production,
    b. Higher stability of flows stimulates the aquatic food base and rainbow trout production

c. Higher volume of flows adds habitat that stimulates the aquatic food base and rainbow trout production.

10) Autochthony plays a lesser role (and thus temporal variation in nutrients may not be as strong a driver) in the lower half of CRe.

11) Fish densities are so low in the lower CRe that SRP does not yet limit population responses.

4. Background

General background

In the CRe, temperature and nutrients are likely to directly drive trends in all aquatic resources identified by the LTEMP (U.S. Department of Interior, 2016a), as well as affecting vegetation colonization on sandbars, and thus potentially affecting the beach resource. The degree to which temperature constrains growth and reproduction of native fish in the CRe has long been recognized (Gorman and VanHoosen, 2000; Robinson and Childs, 2001) as has the potential threat for invasions by nonnative warm-water species that are prevalent in other parts of the Colorado River Basin (Tyus and Saunders, 2000). The desire to manage temperatures in the CRe has led to recommendations for potential flow alterations (e.g., low summer flows) and evaluations of potential infrastructure alterations (e.g., temperature control devices, retrofitting of jet tubes) discussed within the LTEMP BiOp (U.S. Department of Interior, 2016b). However, there is also a growing appreciation for the important interactions between temperature and food availability in ultimately determining fish responses to temperature management (Dodrill and others, 2016). For example, increases in growth rates of fish at optimal temperatures could be cut short if nutrient turnover is not sufficient to augment the aquatic food base to the degree that the energetic demands of fish are met. Historical data from Wahweap suggest that eplimnetic (surface layer) releases from Lake Powell not only are warmer than releases from deeper in the lake, but are likely to deliver lower concentrations of phosphorus, an important limiting nutrient (Vernieu, 2009). A decline in nutrients from the dam could lead to declines in the aquatic food base.

Our understanding of basic patterns of nutrient availability in the CRe, and their significance, is poor, even as there is growing recognition of their potential importance. While both nitrogen and phosphorus are known to be important limiting nutrients in freshwater ecosystems, exceptionally high nitrogen to phosphorus ratios in the CRe suggest that phosphorus is most limiting in this system. Thus, the majority of the work proposed here focuses on better characterizing phosphorus bioavailability and cycling in the river. Phosphorous (specifically SRP) is required by the primary producers (i.e., algae) that serve as the foundation of the aquatic food base. Preliminary data suggest that declines in SRP availability (at the outflow from GCD) over the last five years have propagated through the entire aquatic food web, constraining rates of primary production, invertebrate production, and ultimately suppressing the recruitment of rainbow trout at Lees Ferry and the condition of adult humpback chub near the LCR confluence (Yackulic, 2017). In addition, rainbow trout recruitment since 2001 (when the detection limit for monitoring SRP was lowered to allow for tracking of trends) can be better explained statistically by models that include SRP concentration, than by models that include only flow variables. Currently, a model based on flow variables is used to predict rainbow trout recruitment for the LTEMP, but this model could be significantly improved by incorporating SRP dynamics. An improved understanding of phosphorus dynamics in the CRe could also aid flow-related management. For example, most phosphorous in the CRe is likely to be either bound to carbonates in fine sediments (Elser and others, 1996; Wildman and Hering, 2011) or locked up in biomass (including vegetation, invertebrates, and fish). High flows under the LTEMP, especially HFEs that redistribute sediments and uproot aquatic vegetation and bury it in sediment, have the potential to redistribute phosphorous and alter rates of exchanges with the water column.

Factors affecting spatio-temporal variation in temperature and nutrients in the CRe

Spatio-temporal variation in temperature in the Colorado River downstream from GCD is well understood and primarily driven by the temperature of Lake Powell outflows, air temperature, and discharge. Wright and others (2008) developed a model for predicting water temperature given these drivers in the CRe and this model does an excellent job of predicting temperatures with one important exception. The model overestimates temperatures in downriver reaches during fall low flow months by as much as 2 °C. One factor contributing to this overestimation is that the model assumes linear warming, when exponential warming (in the form $y = a-b*\exp(-x)$) would be expected based on physics. We hypothesize (H1) that replacing the assumption of linear warming with an assumption of exponential warming will lessen the bias in the Wright and others (2008), leading to better predictions of water temperature to predict both native fish responses and potential for invasion and establishment by nonnative warm-water fish.

In contrast to our understanding of spatio-temporal patterns in temperature, our understanding of patterns in nutrients, especially phosphorous and SRP in the CRe is extremely poor. Long-term data on nitrate spanning decades and extending prior to closure of GCD is available at the Grand Canyon gage near Phantom Ranch, and other nutrients are measured occasionally at the Grand Canyon gages near both Bright Angel and Diamond Creeks as well as in some tributaries (U.S. Geological Survey, 2004). Still, SRP has only been measured downstream of Lees Ferry in a few instances (Parnell and others, 1999). SRP concentrations in the Colorado River at Lees Ferry have been regularly measured and generally track measurements taken in the draft intake tubes in GCD (e.g. water from one of the dam penstocks that is actively being used at the time of sampling), as well as at penstock depth in Lake Powell near the dam (e.g. at the Wahweap sampling station). While the large number of estimates at or near detection limits complicates analysis (Figure 1), preliminary analysis suggests that, on average, SRP measurements taken at Lees Ferry differ from measurements in the dam's draft intake tubes by approximately the amount that is required for observed rates of gross primary productivity in Lees Ferry (i.e., 1 µg

L^{-1} drop in SRP concentration assuming average gross primary productivity of 5 g O_2 m^{-2} d^{-1}). This calculation assumes a photosynthetic coefficient of one and that 50% of GPP is respired. Importantly, the average drop is similar in magnitude to the current detection limit, suggesting that measurements of SRP below detection limit indicate severe phosphorous limitation within this reach, let alone at downstream reaches.

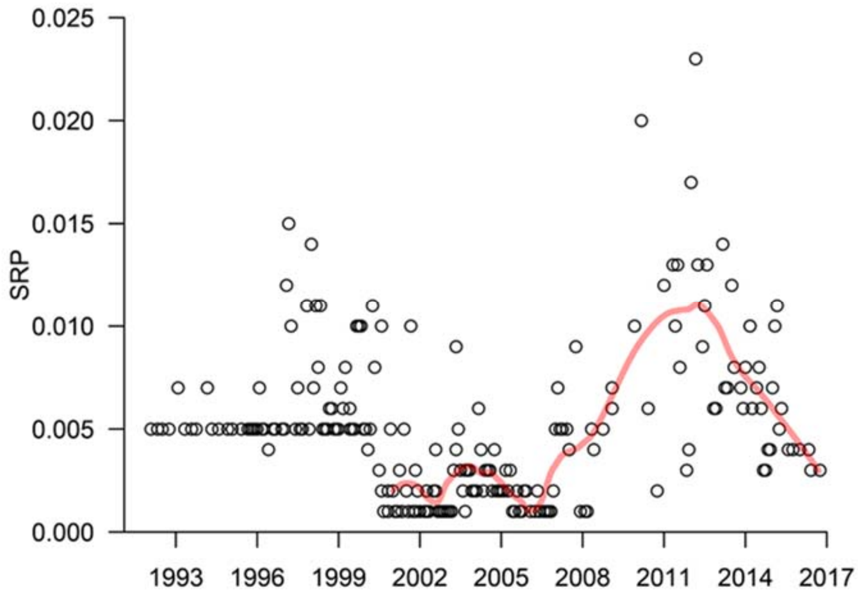

Figure 1. Concentrations of SRP versus date. All data are from the penstock depth at Wahweap and were taken from the Lake Powell historical water quality dataset (Vernieu, 2009). Note the change in analysis detection limit that occurred in 2001. The red line indicates a running average.

A number of processes could potentially modify nutrient cycling downstream of Lees Ferry, leading to either increases or decreases in SRP. We hypothesize (H2) that primary producers will generally remove SRP as water moves longitudinally with greatest losses in the most productive reaches during the day, when turbidity is low. Downstream of the LCR confluence, especially when the LCR is at baseflow, we also hypothesize (H3) that SRP concentrations may decline due to co-precipitation of phosphorous with bicarbonate. This geologic sink for phosphorus has been shown to have a strong influence on phosphorus availability in Arizona streams and can be regulated by rates of primary production and associated effects on pH (Corman and others, 2015, 2016). Understanding pH-related controls on SRP availability is a management-relevant endeavor given the variability in pH observed in the Lake Powell water column (and associated implications for selective withdrawal from Lake Powell). On the other hand, the LCR may serve as a source of SRP at times, particularly when flows are elevated. Storm events that constitute just weeks to months on an annual hydrograph can be responsible for a large fraction of nutrient loading across a variety of stream and river ecosystems (Martin and Harrison, 2011) including in desert systems (Jones and others, 1997). Prior work suggests that the LCR should not contribute substantially to the phosphorus budget of the CRe when at base flow (Moody and Muehlbauer, unpublished data); however, we hypothesize (H4) that flood waters originating in the Paria River and LCR watersheds are a significant source of nutrients, including phosphorous to the CRe. The size of the LCR watershed, and the nutrient intensive human activities and volcanic substrates within it suggest it has the greatest potential to be a nutrient source during storms. Still, given the important role of the Paria River in riverine sediment budgets, and given the high concentrations of Total P that have been measured there (Lawson, 2007), it could also contribute significantly. In addition, we hypothesize (H5) that run-off after forest fires may, at times, provide significant inputs of nutrients, including phosphorous, to the CRe. In particular, large forest fires, such as the recent fire in the Shinumo Creek watershed, have the potential to input significant amounts of phosphorous (Emelko and others, 2016).

Dam operations may also play an important role in spatio-temporal patterns of phosphorous. For example, just as the deltaic sediments in Lake Powell inlets may contribute phosphorous to the water column when they are periodically dried and then wetted, we also hypothesize (H6a) that portions of the river bed that dry during months of lower maximum flows may contribute SRP to the river when they are re-inundated during months of higher maximum flows. In many systems, P release during re-inundation is driven by shifting redox conditions, wherein iron (Fe) bound P is released as sediments go anoxic (Boström and others, 1988; Kinsman-Costello and others, 2014). In the Colorado River, this mechanism is not likely to be very important since Fe bound P makes up only a very small fraction of the total P (based on cores from the Lake Powell sediment delta; Wildman and Hering, 2011). Instead, the mineralization of organic P under dry conditions (when sediments are more aerobic) may produce a sizeable, loosely bound, and easily exchangeable SRP pool that can be mobilized into the water column upon re-inundation. In fact, previous characterization of sediment P fractions in Lake Powell's sediment delta show that a sizeable fraction of P is bound to organic material (Wildman and Hering, 2011). In particular, we expect that varial zones (e.g. zones that are only periodically inundated with water) that are high in organic matter and/or silts and clays could be significant sources of bioavailable phosphorous. To that end, we hypothesize (H6b) that varial zones experiencing significant tamarisk defoliation via tamarisk beetles may result in higher SRP release upon re-inundation. This is based on previous work showing that the presence of tamarisk beetles may substantially change sediment nutrient dynamics (Sankey and others, 2016).

Quantitative links among temperature, nutrients, primary production, and higher trophic levels

Temperature is known to be an important lever on fish bioenergetics, condition and population dynamics in the CRe; however its effects on primary and secondary production are less well understood. For many of the native fish in the CRe, including humpback chub, temperatures above ~12 °C are necessary for growth in length, and temperatures above 15 °C are required for reproduction (Gorman and VanHoosen, 2000; Marsh, 1985). Once these thresholds are exceeded, however, other factors may become important. For example, growth of subadult humpback chub in the LCR does not peak at the warmest time of the year, rather it is greatest when food availability is high during March through May (Dzul and others, 2016). In the CRe, turbidity has an approximately equal role to temperature in explaining the growth of juvenile (Yackulic and others, In Review) and sub-adult humpback chub (Dzul and others, 2016). With respect to rainbow trout, we might expect warming to have a neutral to positive effects on rainbow trout if food were plentiful (well fed rainbow trout should have a temperature preference around 16 °C), however, recent bioenergetics modeling suggests that if the aquatic food base is unchanged, warming will have negative effects on rainbow trout growth and fecundity (Dodrill and others, 2016). Further downstream at Diamond Creek, the aquatic food base is also unlikely to peak with river temperatures since primary production is limited by the highly turbid conditions that occur concomitantly with summertime temperature peaks (Hall and others, 2015). Still, preliminary modeling efforts suggest that seasonal patterns in gross primary productivity (GPP) rates differ from site to site such that the combined effects of nutrients and temperature on fish could vary considerably by location. Taken together, this evidence suggests a need to better understand the drivers of primary and secondary production in the CRe, so as to better understand how different scenarios of warming are likely to benefit, or harm, key aquatic resources identified by the LTEMP EIS, including humpback chub and rainbow trout. In other words, we hypothesize (H7) that the impacts of changes in temperature on the aquatic ecosystem in the CRe will depend crucially on the state of the aquatic food base.

Although aquatic ecosystems are frequently nutrient limited and reservoirs often deplete nutrients, there has been surprisingly little study of how reservoir-induced biogeochemical changes affect downstream riverine ecosystems (Poff and Zimmerman, 2010). In the CRe, we hypothesize (H8) that nutrients, in particular SRP, are important drivers of overall ecosystem productivity, especially in the upstream portion of the CRe (i.e., from GCD downstream to the confluence of the LCR). One reason why H8 has not received more attention in the past, is that variation in SRP has often coincided with unusual dam releases (e.g., SRP began to increase in 2007-2008 coincident with the 2008 Spring HFE, and over the past 16 years, SRP was highest in 2011 and 2012 corresponding to 2011 equalization flows). These releases have led to a number of hypotheses including the hypothesis (H9a) that spring HFEs stimulate the aquatic food base and rainbow trout production, the hypothesis (H9b) that higher stability of flows stimulates the aquatic food base and rainbow trout production, and the hypothesis (H9c) that higher volume of flows adds habitat that stimulates the aquatic food base and rainbow trout production. Modeling of alternative management strategies as part of the LTEMP acknowledged uncertainty in H9a-c, but did not consider the potential importance of nutrients (H8). Importantly, these hypotheses are not mutually exclusive, and there is good corroborating evidence suggesting the important role of spring HFEs in favoring insect over non-insect taxa (H9a, Cross and others, 2013) and of more stable flows leading to increased rainbow trout growth (H9b, Korman and Campana, 2009).

Recent analyses by GCMRC support a potentially important role for H8—that nutrients are an important driver of ecosystem productivity (Deemer and others, unpublished data[4]; Yackulic, 2017). In Lees Ferry, SRP concentration is correlated with invertebrate drift rates and is the single best statistical predictor of rainbow trout recruitment over the last 16 years. In fact, a rainbow trout recruitment statistical model that includes just two predictor variables – the number of adult rainbow trout already in the system in the spring and SRP concentrations – can explain 73% of the variation in recruitment. For comparison, the best statistical prediction model using the number of adults already in the system and various flow metrics representing H9a-c, explains 48% of the variation in recruitment (Yackulic, 2017). In addition to the impacts of nutrients on overall ecosystem productivity, periods of nutrient limitation may also have played a role in the dramatic shifts in the composition of aquatic vegetation community over the last few decades, particularly in the Colorado River in Glen Canyon, where other factors like turbidity play less of a role in limiting gross primary production and shaping aquatic vegetation communities. We hypothesize that during periods of low SRP concentrations, species that can access phosphorous outside of the water column (e.g., rooted macrophytes) will be favored over other species (e.g. Cladophora) that primarily draw nutrients from the water and thrive under higher nutrient concentrations (a hypothesis that could be addressed by the work laid out in Section 7 of this Project, but that is not funded in this work plan).

Downstream from Lees Ferry, near the LCR, we also see recent evidence supporting H8. Since 2012, we have monitored various biological variables near the LCR confluence. SRP concentrations measured at penstock depth in Lake Powell are highly correlated with these biological variables, which include seasonal estimates of primary production, invertebrate drift biomass, and the condition of adults of the three large-bodied native fish species (flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and humpback chub). Furthermore, there have been ~50% declines in rates of spawning of humpback chub in the last two years, coincident with declines in adult fish condition, potentially driven by declining SRP (Yackulic, 2017). The effects of declines in aquatic food base on juvenile humpback chub are less clear and expected to be one emphasis of analyses being undertaken as part of Project G; however, we have some expectation that there may be two broad patterns of fish response to periods of food shortage that transcend humpback chub. Specifically, we hypothesize that fish species and life stages that are well-adapted to persist through periods of food shortage (e.g., adult native fish) will have slower growth, drops in condition, and declines in reproductive output, but will not experience increased mortality, while fish species (e.g., rainbow trout) and life stages (i.e., juvenile native fish) with less fat reserves relative to their metabolic rate will respond more quickly with increased mortality.

[4] Deemer, B.R, C.B. Yackulic, R.O. Hall, T.A. Kennedy, and J.D. Muehlbauer., 2017, Lake Powell nutrient dynamics are a lever on food webs near the LCR—Annual reporting meeting presentation for FY2016—January 26-27, 2017; Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Bureau of Reclamation, Glen Canyon Adaptive Management Program, poster.

While recent work shows a strong link between nutrient concentrations at the Lake Powell penstock depth and ecosystem productivity in the upper part of the CRe, it is unknown how far downstream Lake Powell exerts a measureable influence on riverine nutrient budgets because of the many processes that may be depleting or augmenting SRP concentrations (see Appendix 1). In addition, the downriver CRe has more allochthonous inputs, which leads to the hypothesis (H10) that autochthony plays a lesser role (and thus temporal variation in nutrients may not be as strong a driver) in the lower half of CRe. H10 was not supported by previous food base work throughout the CRe (Cross and others, 2013), which found that diatoms continue to be a significant portion of aquatic insect diets at downriver study locations and the insects remain an important part of fish diets. Interestingly, while most components of the aquatic ecosystem appeared to decline in 2014 in the upper part of the CRe, there is some evidence that humpback chub in the lower part of the CRe (i.e., downstream of Havasu Creek) did very well in 2014. If nutrients are an important ecosystem driver throughout the CRe (i.e., H8 is more supported than H9), then some mechanism must have led to higher SRP in the lower part of the CRe below the LCR (H2-H6), either decreased uptake or increased inputs or both. Alternatively, we might hypothesize (H11) that fish densities are so low in the lower CRe that SRP does not yet limit population responses. Under H11, humpback chub may respond primarily to increases in temperature alone so long as their own densities remain low. However, at some point food limitation must matter so that the long-term prospects for large populations of humpback chub would not seem as promising without increases in primary and second production.

It would not be surprising if humpback chub are currently food-limited near the LCR, and recruitment limited in western Grand Canyon, because of the interactions of temperature and geography. Near the LCR, temperatures in the CRe only need to be warm enough to allow for growth of juveniles because spawning occurs in the LCR. There is some evidence that the portion of the humpback chub population in the Colorado River near the LCR can be recruitment-limited over shorter time scales (1-3 years), but during the recent decline may have been more food-limited. If humpback chub reproduction in the lower CRe occurs within the Colorado River, then temperatures rarely exceed the necessary physiological thresholds leading to recruitment-limitation. Importantly, however, warming temperatures, especially if they occur without increases in the food base, may simply replace the recruitment limitation with a food limitation. If this is the case, we would expect the carrying capacity of a humpback chub population in the western CRe to be substantially lower than that of the population near the LCR.

Larger context of proposed work

As outline above (and in Appendix 1), there are a large number of potentially competing hypotheses pertaining to the controls on ecosystem temperature and nutrient dynamics and their associated effects on higher trophic levels. The large uncertainty surrounding basic patterns in nutrients in the CRe, combined with the potential importance of nutrients as ecosystem drivers throughout the CRe, suggests the need for additional monitoring of nutrients (Project E.1) and more study of the food base in the lower half of the CRe (Project F). Current trends in humpback chub (Project G) and rainbow trout (Project H), potentially driven by declining SRP, also demonstrates the need for more work studying how temperature and nutrients affect ecosystem metabolism (i.e., gross primary production and respiration) and how changes in metabolism affect insect and fish production. The 2016 fisheries Protocol Evaluation Panel (PEP) also identified the need to study how various trophic levels will respond to future conditions, especially the potential for warmer temperature combined with lower nutrients. The following sections illustrate how we will address these needs.

5. Proposed Work

5.1. Project Overview

This project is divided into two elements wherein the first element (E.1.) combined with parallel efforts to better understand nutrient outflows from Lake Powell (see Appendix 1) set the stage for the work proposed in the second element (E.2.). More specifically, the first element (combined with the Lake Powell work in Appendix 1) aims to quantify and describe the most important drivers of temperature and nutrient dynamics in the CRe. By characterizing these patterns and drivers we can compare them to estimates of riverine metabolism conducted in E.2. Ultimately this information about the base of the food web will be combined with aquatic insect and fish data collected in other projects to build whole ecosystem models (also proposed in E.2.).

5.2. Project Elements

Project Element E.1. Temperature and nutrients in the CRe – patterns, drivers, and improved predictions

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Project Description

This project element aims to characterize spatial and temporal patterns in Colorado River temperatures and nutrient availability downstream of GCD as well as to explore several processes that can influence the rate at which bioavailable nutrients are cycled and re-supplied to food webs. To more accurately predict downstream river temperatures in the CRe, an existing model for forecasting river temperatures downstream from the dam will be modified to better predict measured downstream temperatures. To begin characterizing the CRe nutrient budget, the concentrations of various species of N and P will be measured over diel, storm-based, and seasonal timescales and longitudinally in the Colorado River between GCD and western Grand Canyon. Depending on the results of initial assessments of spatial and temporal patterns in FY2018, we may also examine processes that affect nutrient cycling dynamics in later years.

Objectives

1) Modify previous models for predicting CRe temperatures to reflect exponential (rather than linear) warming.
2) Describe spatial and temporal patterns in riverine nutrient availability between GCD and Diamond Creek (including an assessment of the relative importance of tributary nutrient inputs to river nutrient budgets), as well as potential processes driving these patterns.

Methods

Modeling river temperatures in the CRe

Historically, water temperatures near LCR confluence have been too low to allow for reproduction by native fish such as the humpback chub, instead water temperature has mainly influenced fish growth and condition (Dzul and others, 2016; Yackulic and others, 2014). This phenomenon has occurred even in ‘warm’ years (e.g., 2005) in which water temperatures increased by 3-4 °C in summer in response to declining Lake Powell levels. Further downstream, warmer than average years may actually provide for conditions that allow for mainstem reproduction of humpback chub, which is significant given that mainstem reproduction or a second spawning population would be an important step towards humpback chub recovery. As such, predicting reproductive responses of the humpback chub population near the LCR and in western Grand Canyon to management alternatives was a high priority in the LTEMP EIS. We propose to develop an improved temperature model for the CRe based on exponential (rather than linear) warming with increasing distance from GCD to Lake Mead. This model will parse out the influence of air temperature, discharge, and reservoir levels (i.e., discharge temperature) on downstream temperatures based on conditions from the past several decades as well as anticipated future conditions. Water temperature predictions can be used to improve humpback chub reproduction models, but also improve our understanding of how the CRe may change at the ecosystem level in a future warmer and drier climate. This improved model will increase our preparedness to anticipate and respond to future changes in other aspects of the ecosystem including nutrient availability, the food base, and native and non-native fish distributions.

Characterizing spatial and temporal patterns in nutrient availability and studying drivers

Longitudinal sampling will be conducted during each of the four seasons (spring, summer, fall, winter) at 15 sampling sites in the mainstem Colorado River spread relatively evenly between

GCD and Diamond Creek. Sample timing will be carefully determined based on the results of diel (24-hour) sampling—if there is a diel pattern in nutrient availability as has been observed in other systems then we will standardize sampling accordingly. This longitudinal sampling will be compared with longitudinal measurements of both chlorophyll a and ecosystem metabolism (described in Project Element E.3). We will also place refrigerated ISCO automatic water samplers in the Paria River and LCR to capture potential nutrient pulses during storm events. These efforts will begin in the Paria River where sampling is less logistically challenging (and where work is already being conducted as part of Project A). Efforts will be transferred to the LCR mid-way through the work plan once protocols have been solidified. Our plan is to target the Paria River and LCR given that they contribute the majority of tributary discharge between Lake Powell and Lake Mead. If longitudinal sampling suggests that other tributaries or springs may be important with respect to nutrients, we will adjust our plans accordingly. Dependent on our studies of spatial and temporal patterns, we will also conduct a number of studies to better elucidate the drivers of these patterns. Below we detail potential studies, some, or all of which will be undertaken, depending on observed patterns:

1) *Assessing phosphorus bioavailability and co-precipitation potentials:* While SRP is considered the most bioavailable form of phosphorus, bacteria and plants can also access other phosphorus fractions with varying levels of difficulty. Thus, it is important to characterize the quality (e.g. bioavailability) of phosphorus entering the river and not just its total concentration. We may conduct alkaline phosphatase assays to assess the bioavailability of aquatic phosphorus concentrations and the organic matter mineralization sources of bioavailable phosphorus. We may also conduct co-precipitation potential assays on these same samples to determine the relative importance of calcium carbonate precipitation as a phosphorus sink in the river.

2) *Characterizing the role of water level fluctuations for potential riverine P availability and primary production:* If initial sampling suggests this may be an important driver, we will collect nine sediment cores from each of the following habitat types along the CRe: varial zone inundated daily, varial zone inundated seasonally, varial zone inundated high flow. Cores will be subsampled by depth and analyzed for biologically-relevant nutrients.

3) *Assessing the potential role of forest fire in enhancing aquatic nutrient availability:* Large fires in the Colorado River watershed are expected to increase the transport of bioavailable nutrients into the river, particularly phosphorus. If initial sampling suggests that Shinumo Creek has higher concentrations of phosphorous, we will analyze the total phosphorus content of emergent aquatic insects collected along the Colorado River via light trap both upstream and downstream of Shinumo Creek from 2013 to 2015. The sample allows a Before-After-Control-Impact (BACI)-based analysis (before, after, control, experiment) where we can compare total phosphorus

content in insects upstream and downstream of Shinumo Creek both before and after the 2014 wildfire (wherein the upstream data serve as the control).

Project Element E.2. Linking temperature and nutrients to metabolism and higher trophic levels

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Project Description

This project element aims to link information about patterns in riverine nutrients and temperature (gained in Project Elements E.1 and Appendix 1) to higher trophic levels. One aspect of this work will be estimating primary production across the multiple sites within the system at which dissolved oxygen has been monitored in recent years. We will also conduct aquatic vegetation surveys in Glen Canyon to document current conditions and develop an approach for future cost-effective monitoring of aquatic vegetation. In addition, we will conduct artificial stream experiments focused on how primary producers, insects and rainbow trout respond to elevated water temperatures. The final aspect of this element will be development of more integrated models of the aquatic ecosystem. Currently, much research in our work plan is presented in ecological compartments (e.g., invertebrates, rainbow trout, humpback chub). Outside experts and stakeholders have consistently asked for more integration of these components, and recent trends in the ecosystem (particularly in Glen and Marble Canyons) suggest that much could be learned through a more synthetic approach.

Objectives

1) Determine drivers of ecosystem metabolism (including primary production and respiration) throughout the CRe.
2) Document aquatic vegetation composition at fixed sites in Glen Canyon and develop a monitoring scheme to track future changes.
3) Use artificial stream experiments to study how multiple trophic levels may respond to elevated temperatures.
4) Develop ecosystem models linking temperature, nutrients to higher trophic levels.

Methods

Ecosystem metabolism

Primary production in rivers can be estimated from diel patterns of dissolved oxygen. Long-term dissolved oxygen data are available at six sites throughout the Grand Canyon and can be analyzed to yield time-series of primary production. Previously, data from one site, Diamond Creek, was analyzed using semi-mechanistic models to determine drivers of gross primary production (Hall and others, 2015). In addition, the two lead PIs on this project have recently been involved in developing improved estimation models as part of an externally funded national synthesis of primary production estimates from dissolved oxygen probes. We will extend the approach of Hall and others (2015) to the other long-term sites, and consider additional drivers, especially nutrients, in our statistical analyses of the controls on primary production rates. The quality of inferences from these analyses will be improved by undertaking a series of measurements to better calibrate our estimates of ecosystem respiration and gas exchange rates.

We will compare primary production estimates to longitudinal profiles of chlorophyll *a* concentrations in an effort to better understand variation in primary production throughout the whole CRe. Chlorophyll *a* is used in oxygenic photosynthesis and is commonly measured as a metric of ecosystem primary production. While measurements of suspended chlorophyll *a* cannot get at benthic production, we hypothesize that benthic primary production and water column chlorophyll a concentration are positively correlated (and we will examine this hypothesis using available historic and current datasets). Chlorophyll *a* will be measured optically *in vivo* by pumping water from within 1 m of the river surface through the flow through cell on a Turner C3 Submersible Fluorometer (detection limit 0.03 µg/L). Previous chlorophyll *a* sampling in the CRe has shown that chlorophyll *a* concentrations are relatively uniform across depths within the mainstem given how well mixed the river is (Hall personal communication). These measurements will be taken as part of river trips by other projects and may potentially include samples taken by citizen scientists. Longitudinal chlorophyll *a* profiles will be compared to longitudinal measurements of nutrients and additional short-term dissolved oxygen deployments to estimate primary production will be employed if warranted. Estimates of primary production will also be compared to data from other higher trophic levels using ecosystem models.

Aquatic vegetation surveys

In addition to the impacts of nutrients on overall ecosystem productivity, periods of nutrient limitation may also have played a role in the dramatic shifts in the composition of aquatic vegetation community over the last few decades, particularly in the Colorado River in Glen Canyon, where other factors like turbidity play less of a role in limiting gross primary production and shaping aquatic vegetation communities. We hypothesize that during periods of low SRP concentrations in the water column, aquatic algal and plant species that can access phosphorous outside of the water column (e.g., rooted macrophytes) will be favored over species that primarily draw nutrients from the water column (e.g., *Cladophora*). Anglers and scientists alike recognize the dramatic changes that have occurred in the composition and abundance of submerged aquatic vegetation in the GCD tailwater over the last 1-2 decades. Understanding the drivers of these changes, such as the relative importance of flow, dissolved nutrients, and temperature, as well as the current distribution of different vegetation types, requires a relatively cheap surveying method that can easily be repeated at least once each year. During the FY2015-17 work plan we made several advances toward developing a protocol for low-cost surveys of submerged vegetation in the Lees Ferry reach. We developed a new HD underwater video camera system for geolocated video observations of the bed, and used these observations to 1) observe vegetation types at the genus or species level, as well as the depth and substrate they are growing at/on; and 2) develop a high-resolution vegetation mapping system based on acoustic backscatter measured by multibeam sonar. Using backscatter data collected during the 2014 HFE, we have developed a substrate classification for the 25-km reach from GCD to Lees Ferry. Video surveys of selected reaches were also collected in December 2014, October 2015, and August 2016. During these surveys, a low-cost sidescan sonar on a Humminbird fishfinder was used to collect backscatter data and automated data processing techniques were developed for distinguishing between hard/rough and soft/smooth substrates based on the form of echoes received by the sonar (Buscombe, 2017). Work to relate these echo parameters to vegetation presence/absence is showing much promise. In the present work plan we propose to use underwater images from videos/underwater cameras and multibeam sonar systems to carry out aquatic vegetation surveys during the summer of each year. Trips lasting 2-5 days will require just a single boat. The video is required for making detailed, smaller scale species-composition surveys of selected reaches. We will develop a semi-automated genus/species-level vegetation mapping system based on the georectified images collected from video and underwater cameras. This will be used to assess annual to decadal scale changes in vegetative cover, species composition, including invasive weeds. The multibeam sonar system will be used for developing large-scale (15-mile) substrate maps that indicate the presence/absence of vegetation, which will be used for detecting annual-decadal scale changes in vegetation distribution and abundance.

Artificial streams

Under current management policies and projected environmental conditions (U.S. Department of the Interior, 2012), it is likely that river temperatures will exceed the range we currently experiences at some point in the near future with uncertain consequences for the aquatic ecosystem. For example, modelling to support the LTEMP EIS suggested potential for temperatures in the range of 18-22 °C being released through the penstocks within the next twenty years. Predicting how primary producers, invertebrate assemblages, and fish respond to these novel conditions based on modelling of monitoring data is difficult, if not impossible as such approaches are based on observations of current conditions. On the other hand, laboratory studies at a single trophic level (e.g., exposing fish to warm temperatures, but providing them with food items not found in Glen Canyon) may lack the ecological realism required to provide meaningful inferences. Therefore, we propose to use artificial stream experiments to determine how primary producers, invertebrates, and fish respond to variation in water temperature within the current ranges of variation coming from GCD and under scenarios based on potential future conditions in a warmer and drier climate.

Artificial stream experiments will be conducted near the NPS maintenance shop at Lees Ferry. These artificial streams will consist of 12 temporary fiberglass raceways (5 m long x 1 m wide) set up with recirculation and heat pumps to allow manipulation of water temperature. These artificial streams will utilize Colorado River water, representative substrate, primary producers, invertebrates, and fish from the CRe to simulate baseline river conditions. We will quantify changes in nutrient uptake, the biomass, size, and quality of key invertebrate species including midges, blackflies, and mudsnails to experimental conditions and measure the growth and condition of rainbow trout in response to simulated warming. Learning from this initial study, will also be used to plan future work addressing other fish species (e.g., native species) and other conditions (e.g., changes in nutrient conditions associated with withdrawing from the epilimnion).

Ecosystem models

Walters and others (2000) developed a computer-based ecosystem model of immense heuristic value, which helped to identify gaps in monitoring of the CRe at that time and provide basic screening of policy ideas. Over the last 17 years, we have improved monitoring and developed understanding of various components of the CRe through more focused modeling. For example, our understanding of humpback chub population dynamics has improved considerably following adoption of mark-recapture studies (first in the LCR and later in the nearby Colorado River) and associated modeling efforts (Coggins and Walters, 2009; Yackulic and others, 2014; Yackulic and others, In Review). Similarly, food base studies have improved our understanding of trophic interactions (Cross and others, 2013) and led to development of methods for monitoring primary production and invertebrate drift and emergence (Hall and others, 2015; Kennedy and others, 2014). The goal of this project is to develop models of more modest scope than Walters and others (2000) work, but with a broader and more predictive focus than recent work. Recent work has focused on one (or at most two) trophic levels and has been primary descriptive (rather than predictive). This broadening of scope is essential for answering questions about the roles of temperature and nutrients in ecosystem dynamics, for improved understanding of dynamic trophic linkages, and for integrating various diverse sources of data (fish studies, invertebrate studies, primary production estimates, nutrient measurements, etc.) to address hypotheses detailed above, especially hypotheses H8-H11. Broadening the scope of our models should also help us to make better predictions under novel conditions (including a better understanding of uncertainty and gaps in our knowledge). In particular, while the models used to make predictions for the LTEMP EIS were a step in the right direction, they were narrow in their treatment of drivers and representation of ecosystem processes. As such they were more suited for predictions within the range of historically observed conditions (i.e., in the Colorado River near the LCR for temperatures between 8 and 16 °C), than for some of the conditions outside these ranges (e.g., 20 °C near the LCR).

5.3. Deliverables

This work will result in multiple peer-reviewed publications as well as data to support potential management actions by the resource management agencies. While it is difficult to anticipate the full suite of papers that will result from this work (given it is a new focus area), we expect to write peer reviewed papers that address: 1) improved temperature modeling in the CRe, 2) important drivers of nutrient availability in the CRe, 3) spatial patterns and controls on primary production in the CRe, and 4) links between primary production and higher trophic levels in the CRe. Information will also be provided in the form of oral and written presentations to the GCDAMP at the January Annual Reporting Meeting and potentially at more frequent intervals if requested and feasible.

6. References

Allen, A.P., Gillooly, J.F., and Brown, J.H., 2005, Linking the global carbon cycle to individual metabolism: Functional Ecology, v. 19, no. 2, p. 202-213, http://dx.doi.org/10.1111/j.1365-2435.2005.00952.x.

Boström, B., Andersen, J.M., Fleischer, S., and Jansson, M., 1988, Exchange of phosphorus across the sediment-water interface: Hydrobiologia, v. 170, no. 1, p. 229-244, http://dx.doi.org/10.1007/BF00024907.

Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., and West, G.B., 2004, Toward a metabolic theory of ecology: Ecology, v. 85, no. 7, p. 1771-1789, http://dx.doi.org/10.1890/03-9000.

Buscombe, D., 2017, Shallow water benthic imaging and substrate characterization using recreational-grade sidescan-sonar: Environmental Modelling & Software, v. 89, p. 1-18, http://dx.doi.org/10.1016/j.envsoft.2016.12.003.

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—An update considering data from 1989-2008: U.S. Geological Survey Open-File Report 2009-1075, 18 p., http://pubs.usgs.gov/of/2009/1075/.

Corman, J.R., Moody, E.K., and Elser, J.J., 2015, Stoichiometric impact of calcium carbonate deposition on nitrogen and phosphorus supplies in three montane streams: Biogeochemistry, v. 126, no. 3, p. 285-300, http://dx.doi.org/10.1007/s10533-015-0156-6.

Corman, J.R., Moody, E.K., and Elser, J.J., 2016, Calcium carbonate deposition drives nutrient cycling in a calcareous headwater stream: Ecological Monographs, v. 86, no. 4, http://dx.doi.org/10.1002/ecm.1229.

Cross, W.F., Baxter, C.V., Rosi-Marshall, E.J., Hall, R.O., Jr., Kennedy, T.A., Donner, K.C., Wellard Kelly, H.A., Seegert, S.E.Z., Behn, K., and Yard, M.D., 2013, Food-web dynamics in a large river discontinuum: Ecological Monographs, v. 83, no. 3, p. 311-337, http://dx.doi.org/10.1890/12-1727.1.

Dodrill, M.J., Yackulic, C.B., Kennedy, T.A., and Hayes, J.W., 2016, Prey size and availability limits maximum size of rainbow trout in a large tailwater—Insights from a drift-foraging

bioenergetics model: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 5, p. 759-772, http://dx.doi.org/10.1139/cjfas-2015-0268.
Dzul, M.C., Yackulic, C.B., Korman, J., Yard, M.D., and Muehlbauer, J.D., 2016, Incorporating temporal heterogeneity in environmental conditions into a somatic growth model: Canadian Journal of Fisheries and Aquatic Sciences, v.74, p. 316-326, http://dx.doi.org/10.1139/cjfas-2016-0056.
Elser, J.J., Acharya, K., Kyle, M., Cotner, J., Makino, W., Markow, T., Watts, T., Hobbie, S., Fagan, W., Schade, J., Hood, J., and Sterner, R.W., 2003, Growth rate—Stoichiometry couplings in diverse biota: Ecology Letters, v. 6, no. 10, http://dx.doi.org/10.1046/j.1461-0248.2003.00518.x.
Elser, J.J., Dobberfuhl, D.R., MacKay, N.A., and Schampel, J.H., 1996, Organism size, life history, and N:P stoichiometry toward a unified view of cellular and ecosystem processes: BioScience, v. 46, no. 9, p. 674-684, http://dx.doi.org/10.2307/1312897.
Emelko, M.B., Stone, M., Silins, U., Allin, D., Collins, A.L., Williams, C.H.S., Martens, A.M., and Bladon, K.D., 2016, Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems: Global Change Biology, v. 22, no. 3, p. 1168-1184, http://dx.doi.org/10.1111/gcb.13073.
Gorman, O.T., and VanHoosen, R.R., 2000, Experimental growth of four native Colorado River fishes at temperatures of 12, 18, and 24°C—draft final report: Ashland, Wisc., and Willow Beach, Ariz., U.S. Geological Survey, Great Lakes Science Center and U.S. Fish and Wildlife Service, Willow Beach National Fish Hatchery, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 35 p., https://www.gcmrc.gov/library/reports/biological/Fish_studies/USFWS/Gorman2000D.pdf.
Hall, R.O., Yackulic, C.B., Kennedy, T.A., Yard, M.D., Rosi-Marshall, E.J., Voichick, N., and Behn, K.E., 2015, Turbidity, light, temperature, and hydropeaking control primary productivity in the Colorado River, Grand Canyon: Limnology and Oceanography, v. 60, no. 2, p. 512-526, http://dx.doi.org/10.1002/lno.10031.
Jones, J.B., Jr., Schade, J.D., Fisher, S.G., and Grimm, N.B., 1997, Organic matter dynamics in Sycamore Creek, a desert stream in Arizona, USA: Journal of the North American Benthological Society, v. 16, no. 1, p. 78-82, http://dx.doi.org/10.2307/1468238.
Kennedy, T.A., Yackulic, C.B., Cross, W.F., Grams, P.E., Yard, M.D., and Copp, A.J., 2014, The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river: Freshwater Biology, v. 59, no. 3, p. 557-572, http://dx.doi.org/10.1111/fwb.12285.
Kinsman-Costello, L.E., O'Brien, J.M., and Hamilton, S.K., 2014, Re-flooding a historically drained wetland leads to rapid sediment phosphorus release: Ecosystems, v. 17, no. 4, p. 641-656, http://dx.doi.org/10.1007/s10021-014-9748-6.
Korman, J., and Campana, S.E., 2009, Effects of hydropeaking on nearshore habitat use and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society, v. 138, no. 1, p. 76-87, http://dx.doi.org/10.1577/T08-026.1.
Lawson, L., ed., 2007, A water quality investigation of seventeen Grand Canyon tributaries—July 2004-May 2005: Phoenix, Ariz., Arizona Department of Environmental Quality, Division of Water, Surface Water Section, publication no. OFR-07-04, 88 p., http://www.azdeq.gov/environ/water/assessment/download/gcreport.pdf.

Marsh, P.C., 1985, Effect of incubation temperature on survival of embryos of native Colorado River fishes: Southwestern Naturalist, v. 30, no. 1, p. 129-40, http://www.jstor.org/stable/3670666.

Martin, R.A., and Harrison, J.A., 2011, Effect of high flow events on in-stream dissolved organic nitrogen concentration: Ecosystems, v. 14, no. 8, p. 1328-1338, http://dx.doi.org/10.1007/s10021-011-9483-1.

Parnell, R.A., Jr., Bennet, J.B., and Stevens, L.E., 1999, Mineralization of riparian vegetation buried by the 1996 controlled flood, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 225-239.

Poff, N.L., and Zimmerman, J.K.H., 2010, Ecological responses to altered flow regimes—A literature review to inform environmental flows science and management: Freshwater Biology, v. 55, no. 1, p. 194-205, http://dx.doi.org/10.1111/j.1365-2427.2009.02272.x.

Robinson, A.T., and Childs, M.R., 2001, Juvenile growth of native fishes in the Little Colorado River and in a thermally modified portion of the Colorado River: North American Journal of Fisheries Management, v. 21, no. 4, p. 809-815, http://dx.doi.org/10.1577/1548-8675(2001)021<0809:JGONFI>2.0.CO;2.

Topping, D.J., Rubin, D.M., and Melis, T.S., 2007, Coupled changes in sand grain size and sand transport driven by changes in the upstream supply of sand in the Colorado River—Relative importance of changes in bed-sand grain size and bed-sand area: Sedimentary Geology, v. 202, no. 3, p. 538-561, http://dx.doi.org/10.1016/j.sedgeo.2007.03.016.

Tyus, H.M., and Saunders, J.F., III, 2000, Nonnative fish control and endangered fish recovery—Lessons from the Colorado River: Fisheries, v. 25, no. 9, p. 17-24, http://dx.doi.org/10.1577/1548-8446(2000)025<0017:NFCAEF>2.0.CO;2.

U.S. Department of the Interior, 2012, Colorado River Basin water supply and demand study: executive summary: Washington, D.C., Office of the Secretary of the Interior, Bureau of Reclamation, 28 p., http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Executive%20Summary/CRBS_Executive_Summary_FINAL.pdf.

U.S. Department of Interior, 2016, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Geological Survey, 2004, National water information system, water resource data for Arizona online data retrieval—Water years 1949-2004: U.S. Geological Survey Water-Data Report, http://waterdata.usgs.gov/nwis/uv?09380000.

Ulseth, A.J., 2012, Sources, fates, and export of organic carbon in the Colorado River Basin: Laramie, University of Wyoming, Ph.D. in Ecology, unpublished dissertation.

Vernieu, W.S., 2009, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964-2013: U.S. Geological Survey Data Series 471, 23 p., http://dx.doi.org/10.3133/ds471.

Walters, C., Korman, J., Stevens, L.E., and Gold, B., 2000, Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon: Conservation Ecology, v. 4, no. 2, p. 1-38, http://www.consecol.org/vol4/iss2/art1/.

Wildman, R.A., Jr., and Hering, J.G., 2011, Potential for release of sediment phosphorus to Lake Powell (Utah and Arizona) due to sediment resuspension during low water level: Lake and Reservoir Management, v. 27, no. 4, p. 365-375, http://dx.doi.org/10.1080/07438141.2011.632705.

Wright, S.A., Anderson, C.R., and Voichick, N., 2008, A simplified water temperature model for the Colorado River below Glen Canyon Dam: River Research and Applications, v. 25, no. 6, p. 675-686, http://dx.doi.org/10.1002/rra.1179.

Yackulic, C.B., 2017, The role of nutrients in Colorado River ecosystem dynamics—Annual reporting meeting presentation for FY16—January 26-27, 2017: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Bureau of Reclamation, Glen Canyon Adaptive Management Program, https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR20_Yackulic.pdf.

Yackulic, C.B., Korman, J., Yard, M.D., and Dzul, M.C., *in review*, Inferring species interactions through joint mark-recapture analysis: Ecology.

Yackulic, C.B., Yard, M.D., Korman, J., and Van Haverbeke, D.R., 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, v. 4, no. 7, p. 1006-1018, http://dx.doi.org/10.1002/ece3.990.

Yvon-Durocher, G., Caffrey, J.M., Cescatti, A., Dossena, M., Giorgio, P.d., Gasol, J.M., Montoya, J.M., Pumpanen, J., Staehr, P.A., Trimmer, M., Woodward, G., and Allen, A.P., 2012, Reconciling the temperature dependence of respiration across timescales and ecosystem types: Nature, v. 487, no. 7408, p. 472-476, http://dx.doi.org/10.1038/nature11205.

7. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$107,796	$2,000	$34,469	$4,400			$23,128	$171,793
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$67,231	$5,000	$63,302	$3,500	$10,000		$21,929	$170,962
	Total E	**$175,026**	**$7,000**	**$97,771**	**$7,900**	**$10,000**	**$0**	**$45,057**	**$342,754**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$34,026	$2,000	$28,774	$2,400			$17,472	$84,672
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$78,694	$6,000	$21,126	$3,500	$10,000		$28,723	$148,043
	Total E	**$112,720**	**$8,000**	**$49,900**	**$5,900**	**$10,000**	**$0**	**$46,195**	**$232,715**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$35,047	$2,000	$19,627	$2,400			$15,359	$74,433
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$112,131	$4,000	$16,870	$3,500	$10,000		$35,790	$182,291
	Total E	**$147,178**	**$6,000**	**$36,497**	**$5,900**	**$10,000**	**$0**	**$51,149**	**$256,724**

Project F. Aquatic Invertebrate Ecology

1. Investigators

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2. Project Summary

The primary focus of the food base group over the next three years is continuation of long-term monitoring that is needed to evaluate progress toward resource goals identified in the LTEMP. Specifically, we will continue monitoring Colorado River invertebrate drift in Glen and Marble Canyons, which now represent datasets spanning 10 and 6 years, respectively. We will also continue the citizen science light trapping of emergent aquatic insects throughout Marble and Grand Canyons, as well as sticky and light trap monitoring of these insects in Glen Canyon, now in their 6th and 4th years, respectively. All of these long-term monitoring projects provide important baseline information that will be used to determine how the aquatic food base responds to LTEMP flow experiments such as macroinvertebrate production flows. Aquatic insect emergence is a fundamental natural process in rivers, and thus these monitoring data will directly inform progress towards the LTEMP goal for Natural Processes. These food base monitoring data will also provide essential context in support of other LTEMP goals including Humpback Chub, the Rainbow Trout Fishery, Other Native Fish, Nonnative Invasive Species, and Recreational Experience.

We will also evaluate ecosystem responses to macroinvertebrate production flows and other LTEMP flow experiments by initiating drift monitoring at new sites in the Colorado River throughout Glen, Marble, and Grand Canyons during annual food base river trips in the spring and late summer. Most of these new monitoring sites will be adjacent to tributaries, and at the peaks and troughs of midge abundance identified in citizen science emergence monitoring data (e.g., Lees Ferry, Nankoweep, Bright Angel, Tapeats, etc.).

In support of the LTEMP goal for Humpback Chub, we will characterize the quantity of the prey base in the Colorado River at the LCR confluence and in western Grand Canyon (see Project G).

Drift and emergence monitoring will be used to determine the quantity of prey available at these locations. These data on the quantity of prey will be integrated using bioenergetics models, which explicitly account for the effect that water temperature and food availability have on fish physiology.

Research into terrestrial-aquatic linkages will be carried out by our group in support of LTEMP goals for natural processes and tribal resources. The main thrust of this research is a new collaboration with tribal resource trips to monitor bat and bird activity in the CRe. This effort will evaluate the extent to which bat and bird abundance is correlated with the 3-fold variation in midge abundance in Kennedy and others' Bioscience paper (2016). As part of these terrestrial-aquatic linkage studies, we will also continue to support the PhD research of Arizona State University graduate student Christina Lupoli that describes the relative importance of aquatic vs. terrestrial prey to birds, bats, lizards, and rodents (note that ASU covers half of Lupoli's tuition and stipend through a fellowship). This research will identify the extent to which aquatic insect emergence affects the broader CRe, and whether changes in aquatic insect abundance resulting from macroinvertebrate production flows have ecological effects that propagate out of the Colorado River itself.

We will also conduct new research into brown trout feeding habits, prey selection, and bioenergetics in Glen Canyon to determine whether brown trout population increases in this reach are related to recent deterioration of the prey base. This topic was identified as an important research need in the 2017 Food Base Knowledge Assessment.

3. Hypotheses and Science Questions

Some of the hypotheses that Project F will be able to test if macroinvertebrate production flows are conducted in 2018-2020 include:

- H1: Macroinvertebrate production flows increase the abundance of midges in the CRe.
- H2: Macroinvertebrate production flows increase the abundance of EPT (Ephemeroptera, Plecoptera, Trichoptera) in the CRe.
- H3: Macroinvertebrate production flows increase the abundance of swifts, swallows, lizards, bats, and other terrestrial wildlife that are dependent on emergent insects.

If a spring HFE is conducted in 2018-2020, Project F will be able to test the following hypothesis:

- H4: Spring-timed HFEs enhance the food base.

If no HFEs are conducted in 2018-2020, Project F will be able to test the following hypotheses:

- H5: Fall-timed HFEs cause deterioration of the food base vs.
- H6: Fall-timed HFEs have a neutral effect on the food base.

4. Background

The primary focus of food base research and monitoring at GCMRC over the past decade has been on describing drivers and controls of aquatic food webs in the Colorado River in Glen, Marble, and Grand Canyons. The recent culmination of this research has been illuminating because of the strong links that were identified between flow management, the aquatic food base, and the growth and condition of native and desired non-native fish populations. Synoptic food web studies conducted by the food base group demonstrated that the growth, condition, and abundance of rainbow trout in Glen Canyon and native fishes in Grand Canyon were limited by the scarcity of high quality invertebrate prey (Cross and others, 2013; Kennedy and others, 2013). These food web studies also demonstrated that low aquatic insect diversity was contributing to food limitation of fishes in the Colorado River, because 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 (Dodrill and others, 2016; Kennedy and others, 2016). Using multiple lines of evidence, the food base group demonstrated that load-following flows released from GCD were contributing to the absence of EPT taxa and constraining the abundance of midges by causing mortality of aquatic insect eggs laid along unstable river shorelines (Kennedy and others, 2016). Conclusions from this study informed the design of experimental macroinvertebrate production flows, which will be tested as part of implementation of the LTEMP selected alternative.

Macroinvertebrate production flows will involve releasing stable and low flows every weekend during periods of peak aquatic insect egg laying (May-August). Releasing low flows every weekend should ensure that insect eggs laid on weekends remain wetted and are never subject to desiccation prior to hatching, which typically occurs after days to weeks of egg incubation (Merritt and others, 2008; Statzner and Beche, 2010). Ideally, macroinvertebrate flows would be tested in each year of the TWP. Testing macroinvertebrate production flows starting in 2018 has the potential to improve the health of the food base. Further, testing these flows in three consecutive years (i.e., 2018-2020) will represent a more robust test of this potential food base enhancement policy by providing an opportunity for successive cohorts of macroinvertebrates to gradually increase in population over consecutive years, and also minimizing the potential for false conclusions based on only a single yearly test.

Some of the hypotheses that Project F will be able to test if macroinvertebrate production flows are conducted in 2018-2020 include:

- H1: Macroinvertebrate production flows increase the abundance of midges in the CRe.
- H2: Macroinvertebrate production flows increase the abundance of EPT species in the CRe.
- H3: Macroinvertebrate production flows increase the abundance of swifts, swallows, lizards, bats, and other terrestrial wildlife that are dependent on emergent insects.

If macroinvertebrate production flows are tested in 2018-2020, we predict the abundance of midges in drift and light trap samples will increase (H1). These increases may occur within the first year, or in the next spring following the summer in which these flows are tested, because midges are already present in the CRe and have short life cycles with multiple generations per year. Although macroinvertebrate production flows are predicted to enhance midge production throughout the entire CRe, we expect the response to be most pronounced in reaches where the timing of egg laying is out of phase with the timing of daily load-following tides. Specifically, we expect the largest increases in midge abundance in Glen Canyon (river miles -15 to 0), the Upper Granite Gorge (around river miles 90 to 110), and the Lower Canyon (around river miles 190-210). These locations are currently troughs in midge abundance, and under current load-following regimes midges at these locations experience the greatest amount of desiccation induced egg mortality (Kennedy and others, 2016). This hypothesis (H1) and associated predictions will be tested using monitoring described in Project Elements F.1, F.2, and F.4.

If macroinvertebrate production flows are tested in 2018-2020, we also predict the abundance of EPT species captured by drift and light trap sampling will increase (H2). However, a positive EPT response to macroinvertebrate production flows will likely take longer than for midges, because EPT species tend to be larger-bodied and thus longer-lived, with only a single generation per year. Thus, the soonest we would expect long-lived EPT taxa to exhibit an increase would be the year *after* macroinvertebrate flows were first tested. If macroinvertebrate production flows were tested in 2018, then we predict EPT species would begin showing signs of an increase in 2019 at the earliest. Additionally, we expect a positive response from EPT species to macroinvertebrate production flows will be delayed, because these species are exceedingly rare in the CRe and primarily restricted to tributary streams.

Thus, if macroinvertebrate production flows allow EPT species to re-colonize the mainstem CRe, then we expect EPT increases at mainstem locations that are proximate to tributary streams first, and EPT increases at mainstem locations that are distant from tributary streams will occur later. Given these time lags, we also expect that an EPT response to macroinvertebrate production flows will become more likely if the flows are carried out for multiple successive years, rather than over a single summer. This hypothesis (H2) and associated predictions will be tested using monitoring described in Project Elements F.1, F.2, and F.4. It is also hypothesized that improvements in the food base owing to macroinvertebrate production flows will benefit humpback chub, rainbow trout, and other desired fish populations, and monitoring and research described in Projects G and H, in particular, will be used to test these fish-related hypotheses.

If macroinvertebrate production flows are tested in 2018-2020, we predict the number of swifts, swallows, lizards, bats, and other terrestrial wildlife inhabiting the CRe will also increase (H3), because emergent insects are often an important prey resource for these animals. We expect these increases in terrestrial wildlife will mirror any increases in emergent insects, and thus we predict the largest increases in birds and bats will occur in Glen Canyon, the Upper Granite Gorge, and the Lower Canyon, because desiccation induced mortality of insect eggs is greatest at these locations. Similarly, we expect birds, bats and other terrestrial wildlife will respond positively to increases in EPT species, and this will first occur at mainstem locations that are proximate to tributaries. This hypothesis (H3) and associated predictions will be tested using the research described in Project Element F.3.

In addition to persistent structural deficiencies in Colorado River food webs (i.e., low insect diversity, no EPT), the existing food base has been deteriorating since at least 2013. This deterioration is evident across multiple, robust metrics (i.e., five years of invertebrate drift and four years of citizen science light trap monitoring) and across sites spanning the entire CRe (Kennedy, 2017). For example, citizen science aquatic insect emergence monitoring shows a ~ 60% decline in the abundance of adult midges throughout Marble and Grand Canyon from 2012 to 2015. Similarly, invertebrate drift biomass at the LCR confluence declined by ~ 50% between 2012 and 2016 (see Figure). Significantly, recent declines in the condition (plumpness) of humpback chub near the LCR confluence, and declines in the number of spawning humpback chub entering the LCR in spring, are highly correlated with the deteriorating Colorado River food base (Yackulic, 2017). Declines in the condition and abundance of rainbow trout in Glen Canyon are also correlated with declines in invertebrate drift from that location (Korman and others, 2017). Additionally, increases in the abundance of non-native brown trout in Glen Canyon are also correlated with the deteriorating food base (Kennedy, 2017). Owing to the system-wide deterioration of the food base and concomitant declines in the condition of native and desired non-native fish species, the 2017 Food Base Knowledge Assessment group rated the current status and trends of the food base as being of significant concern (http://gcdamp.com/index.php?title=2017_Knowledge_Assessment).

This food base deterioration has occurred coincident with a sequence of four fall HFEs that have been tested since 2012. Demonstrating a causal link between fall HFEs and the deteriorating food base is difficult, because there has been no experimental contrast or control for these experimental flows, such as turning off HFEs for a period of years, or testing a sequence of spring HFEs. Nonetheless, this pattern of a deteriorating food base stands in stark contrast to the dramatically improving food base condition observed for multiple years following the 2008 spring HFE (Cross and others, 2013). Given the apparent negative response of the food base to a sequence of four fall HFEs from 2012-2016, and the contrasting strong positive response of the food base to the 2008 spring HFE, the knowledge assessment working group suggested that testing a spring HFE, or alternatively turning off HFEs for a period of years, were both logical next steps in the adaptive management process.

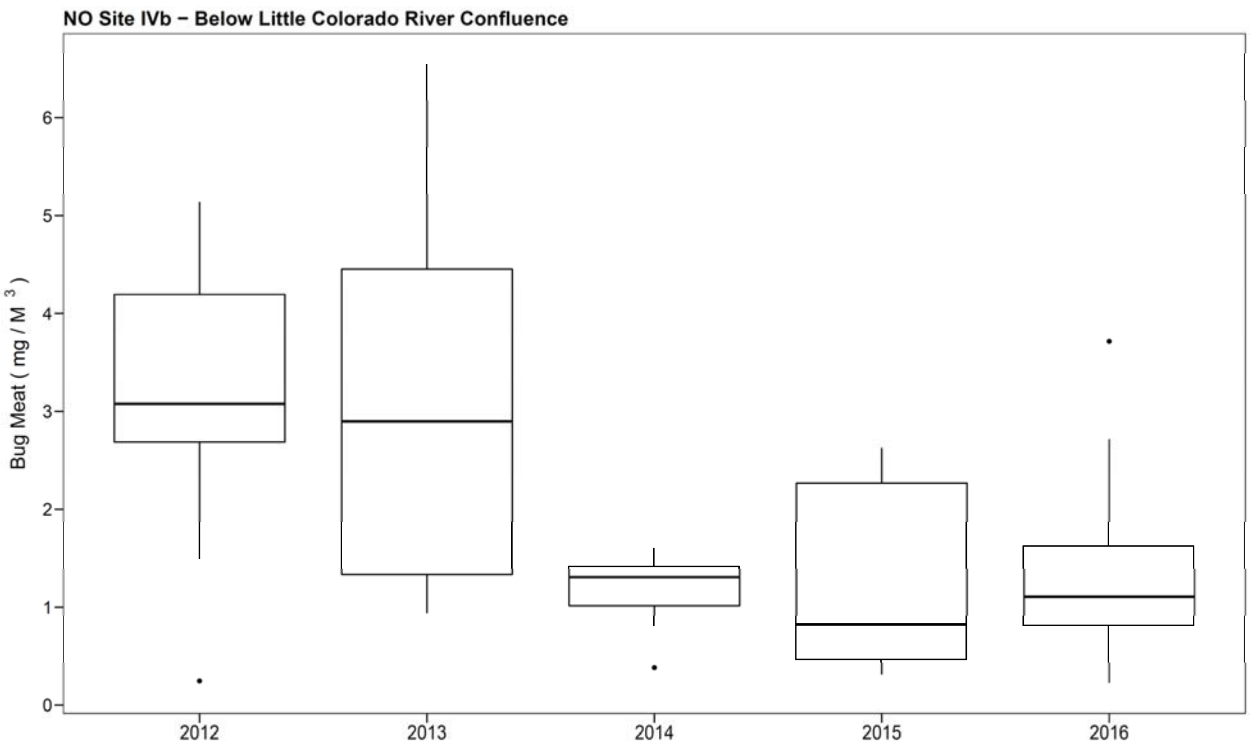

Figure 1. Aquatic macroinvertebrate drift biomass at the LCR Confluence, showing a five year decline in biomass at a reach critical to humpback chub populations.

If a spring HFE is conducted in 2018-2020, Project F will be able to test the following hypothesis:

- H4: Spring-timed HFEs enhance the food base.

If no HFEs are conducted in 2018-2020, Project F will be able to test the following hypotheses:

- H5: Fall-timed HFEs cause deterioration of the food base vs.
- H6: Fall-timed HFEs have a neutral effect on the food base.

HFEs, macroinvertebrate production flows, and the other flow experiments in the selected alternative are intended to aid progress toward the 11 resource goals described in the LTEMP. The aquatic ecology research and food base monitoring described in Project F will be used to directly evaluate progress toward two of these resource goals—Natural Processes and Nonnative Invasive Species. Additionally, research and monitoring described in Project F will provide essential context on the aquatic food base that will inform progress towards other LTEMP

Resource Goals including Humpback Chub, Other Native Fish, Recreational Experience, and the Rainbow Trout Fishery. Project F also includes new research into terrestrial-aquatic linkages that will be done in collaboration with tribal resource trips and will inform progress towards the LTEMP goal for Tribal Resources.

5. Proposed Work

5.1. Project Elements

Project F.1. Influence of dam operations on the food base
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Aquatic invertebrates exhibit movements and behaviors that are ecologically important, not only because these processes are critical to invertebrate life cycles and population dynamics, but because these movements make invertebrates vulnerable to predation by wildlife populations. For instance, although most stream invertebrates are benthic (bottom dwelling), invertebrates are also regularly found drifting with the water current. This process of drift is essential to invertebrate dispersal and colonization and therefore critical to maintenance of populations of these animals (Brittain and Eikeland 1988). Similarly, of the many stream invertebrates that are insects, nearly all transition to becoming winged, air-breathing adults via emergence. Each of these are critical stages in invertebrate life cycles (Huryn and Wallace 2000), but also processes by which they become vulnerable to fishes and terrestrial food webs, often serving as prey for animals like birds, bats, spiders and lizards (Baxter and others, 2005). Increasingly, conditions necessary to support insects not just at the larval stage, but throughout their life cycles (e.g., egg, larvae, pupae, adult) are understood to be important to species management and recovery efforts (Kennedy and others, 2016).

This project element focuses on identifying links between GCD operations and the downstream aquatic food base. We focus our efforts on monitoring invertebrate populations during periods of movement (i.e., emergence and drift), because these drift and emergence data can be used to make inferences about the health and status of invertebrate populations (i.e., Kennedy and others, 2014; Kennedy and others, 2016) and also provide a direct measure of the food base available to humpback chub, rainbow trout, and other wildlife populations (see Projects G and H, especially). The core monitoring described in this project represents the principal data collection effort by which GCMRC will evaluate the efficacy of macroinvertebrate production flows, HFEs, and any other experimental changes to dam operations intended to improve the aquatic food base. If such flow experiments are not implemented, these monitoring efforts still represent an important, long-term dataset that allows us to characterize the status and trends of the aquatic food base, and to evaluate whether the past ~5 years of food base deterioration persist, accelerate, or reverse in the future years.

The main thrust of F.1 is the citizen science monitoring of emergent aquatic insects, where river guides, education groups, private boaters, and other citizen scientists deploy a simple light trap each night in camp to collect samples of adult aquatic insects that have emerged from the Colorado River. This citizen science monitoring has been ongoing since 2012 and has yielded useful insights into the role that dam operations may be playing in the health of the aquatic food base in the CRe downstream of GCD (Kennedy and others, 2016; Metcalfe and others, 2016). Citizen science monitoring of aquatic insects will be an important line of evidence used to evaluate the effectiveness of macroinvertebrate production flows and other LTEMP flow experiments.

Laboratory processing of citizen science light trap samples includes counting and identifying aquatic insects to family or genus, whereas terrestrial insects are identified to order or family. For around 20% of samples, aquatic insect specimens are archived at GCMRC. In January 2017, GCMRC established a memorandum of understanding with Museum of Northern Arizona and Grand Canyon National Park that allows the transfer of terrestrial insect specimens to the Museum of Northern Arizona for identification and archiving. The Museum of Northern Arizona is providing this service at no cost.

We will also monitor invertebrate drift (#/m^3 and g/m^3) in the Colorado River throughout Marble and Grand Canyons during river trips in spring and late summer. As part of these annual monitoring trips, invertebrate drift samples will be collected every 2 miles. This type of strategic monitoring of drift throughout Marble and Grand Canyon will complement more spatially and temporally extensive citizen science monitoring, and will provide another line of evidence for evaluating food base response to LTEMP flow experiments.

We will also continue collaborating with Oregon State University PhD student Erin Abernethy to study the population genetics of aquatic insects native to the Grand Canyon region. Abernethy's role in this study is independently funded through her National Science Foundation Graduate Research Fellowship and by a USGS Graduate Research Improvement grant she and Dr. Jeff Muehlbauer were awarded to carry out this research. This project will entail sampling common aquatic invertebrate species in tributaries throughout Grand Canyon and comparing these populations using genetic sequencing tools that allow comparison of genetic similarity across populations. The results of this genetic analysis will allow us to determine the extent to which populations of common aquatic insects in Grand Canyon tributaries are genetically distinct from one another, as well as the relative time (pre-history, pre-dam, or post-dam) during which any genetic differentiation occurred. Thus, these results will help us understand whether insect species that are currently present in tributaries but absent from the main stem Colorado River in Grand Canyon may have dispersed more readily pre-dam, likely due to the presence of mixing populations in the main stem river, or whether tributary populations were always distinct, indicating that those species likely were not in the mainstem even pre-dam.

Project F.2. Aquatic food base status at humpback chub monitoring locations

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Jeffrey Muehlbauer, Research Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Mike Dodrill, Research Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Recent deterioration of the aquatic food base in Marble Canyon and Grand Canyon and associated declines in the condition (plumpness) and number of spawning humpback chub at the LCR confluence highlight the fundamental role that the aquatic food base plays in the health of native fish populations. This project element is focused on quantifying the food base available to humpback chub and other native fishes. Sampling locations will include sites near the LCR confluence (JCM) and in western Grand Canyon at a new juvenile chub monitoring site (JCM-west; see Project G).

At each of these humpback chub monitoring locations, we will characterize the quantity of prey available by measuring invertebrate drift and insect emergence using light traps and sticky traps. Data on the quantity of the food base will be integrated using a bioenergetics approach to determine levels of consumption (a proxy for how favorable conditions are for growth) at both the LCR confluence and western Grand Canyon (e.g., Dodrill and others, 2016). Use of bioenergetics models will be essential to interpreting these food base data in relation to growth potential for humpback chub across distant sites, because these bioenergetics models explicitly account for the influence of water temperature on fish metabolism (Petersen and Paukert, 2005).

Project F.3. Terrestrial-aquatic linkages

Jeffrey Muehlbauer, Research Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Carol Fritzinger, Citizen science liaison, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Christina Lupoli, Graduate student, Arizona State University, School of Life Science

Insect emergence is a fundamental natural process in streams and rivers. Emerging adult aquatic insects are a key prey item for Colorado River fish populations (Cross and others, 2013; Dodrill and others, 2016), and aquatic insects that successfully emerge from rivers are often the primary prey for terrestrial wildlife including birds, bats, lizards, and rodents (Nakano and Murakami, 2001; Sabo and Power, 2002). Citizen science light trapping is characterizing insect emergence throughout Grand Canyon. In this project element, we will leverage that large dataset to determine the extent to which terrestrial food webs in Grand Canyon are dependent on emerging insects as prey.

We will collaborate with tribal resource trips, educational trips, and other citizen scientists to quantify bat and bird activity throughout Grand Canyon. We will work with tribal participants and river guides to devise a simple and effective protocol for monitoring bat activity and species composition using acoustic monitoring devices (https://www.wildlifeacoustics.com/). These bat activity monitors run on a tablet computer and can identify bats to species based on their calls, and is being piloted on a limited basis in FY2017. This bat monitoring application features an interactive display that allows the user to see, in real-time, the species and numbers of bats that are active during monitoring. The tablet records all this information as a sound file that will be downloaded to a computer at GCMRC once the river trip has concluded. We will also collaborate with tribal resource trips and river guides to develop protocols for quantifying abundance and activity of swallows, swifts, and other types of birds that may be dependent on emergent insects as prey. Protocols for bird monitoring might involve a trained observer making a categorical estimate of swallow and swift abundance along the river (i.e., 0 = no swallows visible, 1 = up to 10 swallows visible, 2 = up to 100 swallows visible, 3 = up to 1000 swallows visible, 4 = more than 1000 swallows visible). These observations of bird activity could be made in camp (e.g., at dawn and dusk) or while river trips are underway (e.g., once per hour while boating). Exact protocols for citizen science monitoring of bat and bird activity will be determined at a later date and in collaboration with citizen scientists. Data on bat and bird activity and species composition will be compared to spatial and temporal patterns of aquatic insect activity as measured by citizen science light trapping to determine the extent to which bats and birds are dependent on emergent insects from the Colorado River. Although these approaches for monitoring bats and birds are may seem simple, they will yield robust data that are powerful enough to detect whether bat and bird activity are correlated with the threefold differences in emergent insect abundance that exist throughout Grand Canyon (Kennedy and others, 2016). Importantly, baseline data on bat and bird activity will also be used to determine whether bat and bird activity increases in the future potentially in response to changes in aquatic insect emergence owing to macroinvertebrate production flows or other LTEMP flow experiments.

As part of this project element, we will also continue to support the PhD research of Arizona State University graduate student Christina Lupoli describing linkages between emergent aquatic insects and terrestrial species such as birds, bats, and lizards that depend on emergent aquatic insects as prey. Funding for Ms. Lupoli's stipend and tuition is jointly provided by Arizona State University (half) and GCMRC (half). GCMRC also supports this research by providing logistics and facilitating her participation on existing river trips. Now in its second year, Ms. Lupoli's research involves use of stable isotope analysis to describe feeding relationships and identify the degree to which terrestrial wildlife along the CRe are feeding on terrestrial vs. aquatic prey. This in-depth investigation of terrestrial food webs and the relative importance of aquatic prey will complement citizen science approaches to bat and bird monitoring described above. Collectively, these studies will identify whether changes in aquatic insect abundance owing to macroinvertebrate production flows cascade out of the Colorado River itself.

Project F.4. Glen Canyon aquatic food base monitoring and research

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Jeffrey Muehlbauer, Research Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element is a continuation of a monthly Glen Canyon monitoring program that has been ongoing for up to 10 years, representing a valuable long-term dataset for identifying status and changes in the aquatic food base. Specifically, as part of this monitoring program we sample aquatic invertebrate drift at ten sites from GCD to the head of Badger Rapid (RMs -13.0, -11.0, -8.0, -4.9, -3.5, -2.1, 0, 1.7, 3.3, and 6.0), which allows us to understand and model changes in invertebrate drift over time and also in response to flow conditions such as riffles, pools, and tributary sediment inputs from the Paria River.

In addition to drift sampling, this monitoring program includes monthly sticky and light trap sampling of emergent adult aquatic insects that has been ongoing since 2013. In this work plan, we propose to sample at a reduced number of sites compared to previous years because a recent analysis of the dataset indicates sampling effort could be reduced without a significant loss in statistical power (Muehlbauer, 2017a). Accordingly, we will reduce effort to 17 sticky sites and 4 light trap sites approximately evenly-spaced from GCD to the head of Badger Rapid. This reduction in effort will lower costs and still allow us to identify patterns and trends in adult aquatic insect emergence throughout Glen Canyon and upper Marble Canyon over time and in space. Emergent insects on land are more easily sampled than drift and benthic larvae in the river and yet tend to respond proportionally to changes in benthic insect abundance stemming from environmental variation and other conditions (Statzner and Resh, 1993). Continuing to sample aquatic insects using multiple methods that collect drifting or emergent life stages in Glen Canyon enables quantification of the drift-emergent insect relationship in the CRe. This, in turn, allows us to continue to make strong predictions about the food base available to support Colorado River native fish populations in Marble and Grand Canyons, where citizen science light trapping occurs infrequently and where regular measurements of invertebrate drift are infeasible.

This monitoring is carried out using published methods developed by the food base group (Baxter and others, 2017; Copp and others, 2014; Kennedy and others, 2013; Kennedy and others, 2014; Muehlbauer and others, 2017b; Smith and others, 2014). Due to the consistency in sampling methodologies, these data also allow us to compare aquatic food base conditions in Glen Canyon to those in Marble and Grand Canyon (see Project Elements F.1 and F.2).

Project F.5. Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?

Mike Dodrill, Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project element are to 1) compare and contrast prey utilization and selection by rainbow trout and brown trout and 2) use this information on trout foraging ecology to model and predict how these two species will respond to changes in the physical template of Glen Canyon (e.g., increases in water temperature) and changes in the prey base (e.g., New Zealand mudsnails vs. aquatic insects).

This project element will utilize the long-term invertebrate drift monitoring data described in Project F.4 to characterize the prey resources available to foraging rainbow trout and brown trout in Glen Canyon over time. This information on prey availability will be combined with diet data to contrast how these two salmonids utilize prey resources. Prior food web studies in Glen Canyon demonstrated that midges and black flies were key prey items for rainbow trout (Cross and others, 2011). Recent bioenergetics modeling (Dodrill and others, 2016) and prey selection analyses (Dodrill, unpublished data) also point to the importance of black flies and midges in fueling rainbow trout growth and condition. Less is known about the foraging ecology of brown trout in Glen Canyon, but preliminary diet data indicate brown trout utilize more benthic prey types compared to rainbow trout (i.e., brown trout appear to preferentially prey upon New Zealand mudsnails and *Gammarus*). Since around 2013 the food base in Glen Canyon has been dominated by New Zealand mudsnails and other types of benthic prey (e.g., tubificid worms, *Gammarus*), while aquatic insects have been exceedingly rare, potentially as a result of repeated testing of fall HFEs that began in 2012. Thus, recent declines in the abundance of aquatic insects and a shift in the food base towards New Zealand mudsnails may actually be facilitating the expansion of brown trout populations in Glen Canyon. Additionally, these undesirable shifts in the prey base may be exacerbating the negative effects of intra-specific competition for aquatic insects on the health and condition of rainbow trout populations in Glen Canyon (Korman and others, 2017).

This project element will describe the trophic ecology of rainbow trout and brown trout, which contributes to broader ecosystem modeling goals described in Project E. Additionally, information on prey selection patterns and observed shifts in the food base composition will be used to estimate growth potential for brown trout vs. rainbow trout under different prey availability scenarios (i.e., a prey base dominated by aquatic insects, as observed in 2008-2010, compared to the current prey base dominated by New Zealand mudsnails). Bioenergetics models will also be used to forecast growth potential for brown trout and rainbow trout under the different water temperature scenarios that were used in LTEMP modeling. These types of mechanistic approaches have been successfully applied in past research to understand how prey availability and water temperature determines the lifetime growth potential of rainbow trout (Dodrill and others, 2016). This project will build on those recent efforts and identify whether shifts in the prey base and changing water temperatures have the potential to favor brown trout over rainbow trout.

5.2. Deliverables

Project F will evaluate food web response to macroinvertebrate production flows, HFEs, and other LTEMP flow experiments. Each of the five project elements will result in one or more peer-reviewed journal articles and presentations at scientific meetings. These project elements describe cutting-edge work in applied aquatic ecology, and the outcome of several of these project elements will be the publication of papers in the highest-tier scientific journals. We will also provide summaries of key food base monitoring metrics (e.g., light trap catches, EPT abundance, long-term drift in Lees Ferry, etc.) at the Annual Reporting Meeting each January. Additionally, we can provide more frequent summaries of key monitoring metrics, contingent upon sample processing progress, if there is interest in evaluating the initial food base response to any LTEMP flow experiments.

6. References

Baxter, C.V., Kennedy, T.A., Miller, S.W., Muehlbauer, J.D., and Smock, L.A., 2017, Macroinvertebrate drift, adult insect emergence and oviposition, *in* Hauer, F.R., and Lamberti, G.A., eds., Methods in Stream Ecology, vol. 1, 3rd edition, Ecosystem Structure: Academic Press, p. 435-456, http://dx.doi.org/10.1016/B978-0-12-416558-8.00021-4.

Baxter, C.V., Fausch, K.D., and Saunders, W.C., 2005, Tangled webs—Reciprocal flows of invertebrate prey link streams and riparian zones: Freshwater Biology, v. 50, no. 2, p. 201–220, http://dx.doi.org/10.1111/j.1365-2427.2004.01328.x.

Brittain, J.E., and Eikeland, T.J., 1988, Invertebrate drift—A review: Hydrobiologia, v. 166, no. 1, p. 77-93, http://dx.doi.org/10.1007/BF00017485.

Copp, A.J., Kennedy, T.A., and Muehlbauer, J.D., 2014, Barcodes are a useful tool for labeling and tracking ecological samples: Bulletin of the Ecological Society of America, v. 95, no. 3, p. 293-300, http://dx.doi.org/10.1890/0012-9623-95.3.293.

Cross, W.F., Baxter, C.V., Donner, K.C., Rosi-Marshall, E.J., Kennedy, T.A., Hall, R.O., Jr., Wellard-Kelly, H.A., and Rogers, R.S., 2011, Ecosystem ecology meets adaptive management—Food web response to a controlled flood on the Colorado River, Glen Canyon: Ecological Applications, v. 21, no. 6, p. 2016-2033, http://dx.doi.org/10.1890/10-1719.1.

Cross, W.F., Baxter, C.V., Rosi-Marshall, E.J., Hall, R.O., Jr., Kennedy, T.A., Donner, K.C., Wellard Kelly, H.A., Seegert, S.E.Z., Behn, K., and Yard, M.D., 2013, Food-web dynamics in a large river discontinuum: Ecological Monographs, v. 83, no. 3, p. 311-337, http://dx.doi.org/10.1890/12-1727.1.

Dodrill, M.J., Yackulic, C.B., Kennedy, T.A., and Hayes, J.W., 2016, Prey size and availability limits maximum size of rainbow trout in a large tailwater—Insights from a drift-foraging

bioenergetics model: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 5, p. 759-772, http://dx.doi.org/10.1139/cjfas-2015-0268.
Huryn, A.D., and Wallace, J.B., 2000, Life history and production of stream insects: Annual Review of Entomology, v. 45, p. 83-110, http://coweeta.uga.edu/publications/1436.pdf.
Kennedy, T.A., 2017, Floods, flows, and the aquatic foodbase—Technical Work Group annual reporting meeting presentation: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, available at https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR19_Kennedy.pdf.
Kennedy, T.A., Cross, W.F., Hall, R.O., Jr., 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: U.S. Geological Survey Fact Sheet 2013-3039, 4 p., http://pubs.usgs.gov/fs/2013/3039/.
Kennedy, T.A., Muehlbauer, J.D., Yackulic, C.B., Lytle, D.A., Miller, S.W., Dibble, K.L., Kortenhoeven, E.W., Metcalfe, A.N., and Baxter, C.V., 2016, Flow management for hydropower extirpates aquatic insects, undermining river food webs: BioScience, v. 66, no. 7, p. 561-575, http://dx.doi.org/10.1093/biosci/biw059.
Kennedy, T.A., Yackulic, C.B., Cross, W.F., Grams, P.E., Yard, M.D., and Copp, A.J., 2014, The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river: Freshwater Biology, v. 59, no. 3, p. 557-572, http://dx.doi.org/10.1111/fwb.12285.
Korman, J., and Yard, M.D., 2017, Trends in rainbow trout recruitment, abundance, survival, and growth during a boom-and-bust cycle in a tailwater fishery: Transactions of the American Fisheries Society, early view, available online at http://dx.doi.org/10.1080/00028487.2017.1317663.
Merritt, R.W., Cummins, K.W., and Berg, M.B., eds., 2008, An introduction to the aquatic insects of North America (4th ed.): Dubuque, Iowa, Kendall Hunt Publishing Co.
Metcalfe, A.N., Kennedy, T.A., and Muehlbauer, J.D., 2016, Phenology of the adult angel lichen moth *(Cisthene angelus)* in Grand Canyon, USA: The Southwestern Naturalist, v. 61, no. 3, p. 233-240, http://dx.doi.org/10.1894/0038-4909-61.3.233.
Muehlbauer, J.D., 2017a, Fluvial aquatic ecology of the Colorado River (...especially Lees Ferry)—Technical Work Group annual reporting meeting presentation: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center available at https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR18_Muehlbauer.pdf.
Muehlbauer, J.D., Kennedy, T.A., Copp, A.J., and Sabol, T.A., 2017b, Deleterious effects of net clogging on the quantification of stream drift: Canadian Journal of Fisheries and Aquatic Sciences, v. 74, no. 4, p. 1041-1048, http://dx.doi.org/10.1139/cjfas-2016-0365.
Nakano, S., and Murakami, M., 2001, Reciprocal subsidies—Dynamic interdependence between terrestrial and aquatic food webs: Proceedings of the National Academy of Sciences, v. 98, no. 1, p. 166-170, http://www.pnas.org/content/98/1/166.full.
Petersen, J.H., and Paukert, C.P., 2005, Development of a bioenergetics model for humpback chub and evaluation of water temperature changes in the Grand Canyon, Colorado River: Transactions of the American Fisheries Society, v. 134, no. 4, p. 960-974, http://dx.doi.org/10.1577/T04-090.1.
Sabo, J.L., and Power, M.E., 2002, River-watershed exchange—Effects of riverine subsidies on riparian lizards and their terrestrial prey: Ecology, v. 83, no. 7, p. 1860-1869, http://dx.doi.org/10.1890/0012-9658(2002)083[1860:RWEEOR]2.0.CO;2.

Smith, J.T., Kennedy, T.A., and Muehlbauer, J.D., 2014, Building a better sticky trap—Description of an easy-to-use trap and pole mount for quantifying the abundance of adult aquatic insects: Freshwater Science, v. 33, no. 3, p. 972-977, http://dx.doi.org/10.1086/676998.

Statzner, B., and Resh, V.H., 1993, Multiple-site and -year analysis of stream insect emergence—A test of ecological theory: Oecologia, v. 96, no. 1, p. 65-79, http://dx.doi.org/10.1007/BF00318032.

Statzner, B., and Bêche, L.A., 2010, Can biological invertebrate traits resolve effects of multiple stressors on running water ecosystems?: Freshwater Biology, v. 55, no. s1, p. 80-119, http://dx.doi.org/10.1111/j.1365-2427.2009.02369.x.

Yackulic, C.B., 2017, The role of nutrients in Colorado River ecosystem dynamics—Annual reporting meeting presentation for FY16—January 26-27, 2017: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Bureau of Reclamation, Glen Canyon Adaptive Management Program, https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR20_Yackulic.pdf.

7. Budget

The bulk of the funding requested will be used to cover salaries of investigators and technicians. Specifically, the funding requested will support two fulltime Ph.D. investigators (Kennedy GS13, Muehlbauer GS12) and one halftime M.S. investigator (Dodrill, GS9) needed to analyze and interpret food base data. The funding requested will also support 4 fulltime technicians (GS 7) and 2 half-time technicians (GS 3) needed for field data collection and annual laboratory processing of approximately 1000 light trap samples, 750 drift samples, 500 sticky trap samples, and dozens of rainbow and brown trout diet samples. The requested funding also provides a modest stipend (~$15/sample) to citizen scientists collecting light trap samples (see Operating Expenses), funding for two 1-boat river trips per year staffed by 2 scientists to collect high resolution drift samples throughout Marble and Grand Canyon (see Logistics, $10,000 per trip), and partial salary stipend and tuition coverage in 2018 and 2019 for ASU graduate student Christina Lupoli (see Cooperators, non-USGS-F.3).

		Fiscal Year 2018							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
F	***Aquatic Invertebrate Ecology***								
F.1	Influence of dam operations on the food base	$294,337	$6,650	$26,000	$20,000	$8,000		$54,221	$409,208
F.2	Aquatic food base status at humpback chub monitoring locations	$97,174						$15,117	$112,291
F.3	Terrestrial-aquatic linkages	$19,571		$1,700		$26,250		$4,097	$51,618
F.4	Glen Canyon aquatic food base monitoring and research	$80,067	$12,500	$4,000				$15,023	$111,590
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$71,390	$2,500	$1,000				$11,651	$86,541
	Total F	**$562,539**	**$21,650**	**$32,700**	**$20,000**	**$34,250**	**$0**	**$100,108**	**$771,248**

		Fiscal Year 2019							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
F	***Aquatic Invertebrate Ecology***								
F.1	Influence of dam operations on the food base	$295,291	$6,850	$26,000	$20,600			$90,673	$439,414
F.2	Aquatic food base status at humpback chub monitoring locations	$92,995						$24,179	$117,174
F.3	Terrestrial-aquatic linkages	$20,158		$1,751		$27,038		$6,507	$55,454
F.4	Glen Canyon aquatic food base monitoring and research	$82,469	$12,875	$4,120				$25,861	$125,325
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$56,152	$2,400					$15,224	$73,776
	Total F	**$547,065**	**$22,125**	**$31,871**	**$20,600**	**$27,038**	**$0**	**$162,443**	**$811,143**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
F	*Aquatic Invertebrate Ecology*								
F.1	Influence of dam operations on the food base	$302,261	$7,055	$26,000	$21,218			$92,699	$449,233
F.2	Aquatic food base status at humpback chub monitoring locations	$97,353						$25,312	$122,665
F.3	Terrestrial-aquatic linkages							$0	$0
F.4	Glen Canyon aquatic food base monitoring and research	$88,958	$13,261	$4,244				$27,680	$134,143
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$58,620						$15,241	$73,861
	Total F	**$547,192**	**$20,316**	**$30,244**	**$21,218**	**$0**	**$0**	**$160,932**	**$779,902**

8. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Elements F.(i). Sampling that was eliminated owing to budget reductions includes:

- all benthic monitoring
- all humpback chub diet analysis
- all quagga mussel monitoring
- all food base work in tributaries
- all research into potential effects of fall HFEs on the food base (e.g., rock scrubs, lateral variation in drift, *Gammarus* synthesis)

Project G. Humpback Chub Population Dynamics throughout the Colorado River Ecosystem

1. Investigators

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service
David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
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Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary

Monitoring and research activities associated with humpback chub are mostly mandated by BiOp associated with the LTEMP EIS, which provides limited flexibility for additional work. Within these constraints, proposed activities also seek to respond to recommendations made by the August 2016 Fisheries PEP including: 1) focusing inferences on open models and vital rates (movement, growth, and survival), rather than solely abundance, 2) improving the efficiency of humpback chub research, 3) considering additional, hypothesis-driven research into recent increases in the lower half of the CRe, and 4) critically examining the effectiveness of translocation programs. Lastly, to the extent possible, analyses and research are responsive to recent trends and hypothesized drivers.

Since the fall of 2014, adult humpback chub in the Colorado River near the LCR have had reduced condition factor (the ratio of the observed weight to the predicted weight based on length), lower spawning rates relative to earlier years, and juvenile chub abundances have declined precipitously (Yackulic, 2017). While there is good evidence that turbidity, temperature, and negative interspecific interactions drive vital rates, we hypothesize that these recent declines may have been driven by a fourth factor – a depressed aquatic food base. This hypothesis will be one focus of modeling efforts related to humpback chub population dynamics during FY2018-20. In contrast to the deteriorating conditions near the LCR, there is evidence of increased catch of multiple size classes of humpback chub in the Colorado River in western Grand Canyon in recent years. The drivers of these changes are not well understood in part due to the fact that sampling in western Grand Canyon does not allow for estimation of fish condition, vital rates, or abundance.

Humpback chub monitoring and research includes both work within the LCR and in neighboring reaches of the Colorado River, where densities of humpback chub are greatest, and in less dense aggregations both upstream and downstream of the LCR confluence. Humpback chub monitoring near the LCR involves sampling both in the tributary itself and at a site in the Colorado River downstream from the LCR confluence known as the JCM site. U.S. Fish and Wildlife Service (USFWS)-led sampling in the LCR will maintain the same effort (two fall trips and two spring trips) and will continue to yield abundance estimates from closed models. Effort associated with the JCM project will be decreased and we will modify our protocol (increasing the size of the study reach, moving hoopnets more frequently, integrating remote antennas and focusing sampling during months when capture probability should be highest) with the goal of maintaining acceptable precision on vital rates and adult humpback abundances that are derived from open multistate models that integrate data from the LCR and JCM monitoring. We are testing less expensive technology to track humpback chub movement into the LCR and will continue to work to integrate these data into population models; however, less staff time will be available for population modeling in this work plan and goals for progress in population modeling have been modified accordingly. Aggregation sampling in the Colorado River outside of the LCR will occur as in the past. To explore the feasibility of hypothesis-driven research outside of the LCR, we will apply JCM sampling at a site downriver of the LCR to determine whether JCM sampling can lead to estimates of capture probability, abundance and vital rights (and ultimately strong inferences on drivers) at sites that likely have lower densities, but higher capture probabilities. Lastly, translocations about Chute Falls will continue as in the past, and a feasibility study will be conducted to determine whether translocations into the upper reaches of Havasu Creek are possible.

3. Hypotheses and Science Questions

1) Temporal variation in food availability leads to temporal variation in the carrying-capacity of the CRe for juvenile humpback chub and that the interaction between this carrying capacity and actual densities affects humpback chub growth and survival.
2) Humpback chub growth in terms of length and weight are asynchronous due to asynchrony in the CRe between temperature and food availability.
3) Humpback chub are in poor condition and are spawning at a lower rate.
4) There had been a massive decline in the adult humpback chub population. Such a decline in adult survival could hypothetically have occurred in the mainstem (H4a) or in the LCR (H4b).
5) Humpback chub densities are still so low in the lower half of the river that food limitation is not yet an important factor, but will become one if populations continue to recover – with implications for establishing a second population.
6) Humpback chub in the lower half of the river are not as dependent on autochthonous production (i.e., diatoms in the river that require SRP and that in turn are the main

food of the aquatic insects on which humpback chub feed), and thus are less affected by the amount of SRP in dam releases (see Project E).

7) There are sources of SRP downstream of the Little Colorado River in 2014, such that autochthonous production did not decline as substantially in the lower half of the Colorado River as they did in Glen and Marble Canyons.
8) Frequent HFEs over the last four years have exported large quantities of aquatic vegetation biomass to the lower half of the CRe fueling recent increases in humpback chub population.
9) Chute Falls translocation is adding a sufficient number of adults to the population to justify the costs.

4. Background

Humpback chub that spawn in the LCR

Since 2001, mark-recapture monitoring led by USFWS in the LCR has formed the backbone of monitoring for humpback chub that spawn in the LCR (Coggins and others, 2006; Van Haverbeke, 2013). Humpback chub have much higher capture probabilities in the LCR making it is easier to estimate spawning (spring) and resident (fall) adult abundances. The data from this mark-recapture monitoring is used to estimate sub-adult population estimates which are one of the conditions that can trigger non-flow management actions mandated by the BiOp, and provides a large amount of the data necessary to estimate total adult abundance, another important estimate which can trigger non-flow management actions. The data provided by this effort is necessary, but not sufficient, to estimate total adult abundances because humpback chub skip-spawn (i.e., adults do not spawn every year; Pearson and others, 2015; Yackulic and others, 2014). As a result of skip-spawning, some portion of the adult population is not available for capture in the LCR in any given year. Estimating the total abundances with LCR-based data alone requires one of two assumptions:

1) The probability that any given individual is present in the LCR in the fall or spring of a given year is independent of whether it was present in the prior spring or fall.
2) The survival and growth probabilities in the LCR and CRe are the same.

Both assumptions are now known to be violated, with the first assumption grossly violated (Yackulic and others, 2014). The first assumption is implicit in any modeling approach that does incorporate temporary emigration or spatial location (i.e., CRe versus LCR,), and violation of this assumption can lead to negative bias in abundance estimates (Kendall and others, 1997) and the appearance of declines in total abundance that actually represent changes in the rate of spawning. If spawning rates decline and then increase, violation of this assumption should lead to unstable estimates of abundance as additional years of data are collected (i.e., retrospective bias; Coggins and others, 2009). Thus the complexity of the life history of humpback chub that spawn in the LCR necessitates that we also sample in the CRe and include spatial locations in our models so long as managers remain interested in accurate estimates of total adult abundance.

Since 2009, mark-recapture studies in the Colorado River near the LCR confluence (i.e., the near shore ecology study from 2009 to 2011 and the JCM study from 2012 onwards) have led to a much improved understanding of the population dynamics of humpback chub that spawn in the LCR. These studies have led to insights into how rainbow trout and environmental conditions affect the growth and survival of juvenile humpback chub (Dzul and others, 2016; Yackulic and others, *in press*), allowing for better understanding of the likely consequences of different management alternatives, including different flows and mechanical removal. With respect to rainbow trout, analyses consistently find evidence that increasing rainbow trout abundances are associated with both lower survival and capture probability of juvenile humpback chub, with less consistent evidence for lowered growth of juvenile humpback chub in the presence of higher rainbow trout abundances. While these relationships are consistent (i.e., they are statistically significant even when different subset of data are analyzed independently), the magnitude of the negative effect is still uncertain. Furthermore, rainbow trout only explain a modest amount of the variation in survival, growth, and capture probabilities. For example, even when other environmental factors (e.g., temperature, turbidity) are included in mark-recapture models, less than 50% of the variation in both survival and growth is explained (Yackulic and others, *in press*).

Work so far suggests that if there were consistently half as many rainbow trout near the LCR, we would expect approximately 25% more adult humpback chub at equilibrium, with 95% credible intervals spanning 1% to 59% more adult humpback chub (Yackulic and others, *in press*). While this prediction is insensitive to mean annual juvenile production in the LCR, the exact equilibrium abundance of adult humpback chub is extremely sensitive to juvenile production. If juvenile humpback chub production in the LCR is relatively high (e.g., 25,000 juveniles in July in the LCR), there may be no need to take action to reduce rainbow trout abundance in the CRe mainstem near the LCR confluence to maintain a population of humpback chub greater than 5,000 adults over the long term. On the other hand, if juvenile humpback chub production in the LCR is relatively low (e.g., 15,000 individuals in the LCR in July), reducing rainbow trout abundance in the CRe mainstem near the LCR confluence may be essential to maintain a humpback chub populations above 5,000 adults (Yackulic and others, *in press*). Direct estimates of juvenile humpback chub production in the LCR over the last few years have been low (~14,000), however, this covers a short time period and there has been extreme year to year variation (e.g., ~25,000 in 2015 followed by ~3,000 in 2016), necessitating additional study of juvenile humpback chub production. Importantly, juvenile outmigration occurs primarily between July and September (Yackulic and others, 2014) and the majority of juveniles that leave the LCR do not enter the JCM reach, making it difficult to interpret humpback chub production based solely on fall age 0 humpback chub estimates in the LCR and fall juvenile humpback chub abundances in the JCM.

Even if annual juvenile humpback chub production in the LCR is low, it is highly unlikely that rainbow trout will extirpate humpback chub in the LCR aggregation in the absence of additional stressors (Yackulic and others, *in press*). We note, however, there remains considerable uncertainty in this prediction given that halving rainbow trout abundance could lead to a wide range of responses from no appreciable increase in adult humpback chub to as much as a 59% increase in adult abundances (Yackulic and others, *in press*). This uncertainty arises, in part, because the combination of rainbow trout abundance, temperature, and turbidity explains only 43% of variation in juvenile humpback growth and only 38% of the variation in juvenile humpback chub survival. This suggests that our understanding of drivers of juvenile humpback chub dynamics is still not sufficient. Attempting to incorporate density-dependence (Yackulic and others, *in press*) or drift densities (Dzul and others 2016, Yackulic, USGS unpublished) as additional covariates in a regression context does not improve statistical prediction. However, it is possible that different structural assumptions (i.e., besides those implicit in a typical regression) could lead to improved understanding and predictive ability.

In FY2018-20, we will focus on testing a series of hypotheses related to the interactions of juvenile humpback chub densities, food availability, and temperature on juvenile humpback chub growth and survival. In particular, we will test the hypothesis (**H1**) that temporal variation in food availability leads to temporal variation in the carrying-capacity of the CRe for juvenile humpback chub and that the interaction between this carrying capacity and actual densities plays an important role in determining humpback chub growth and survival. We will also seek to incorporate weight data directly into our models to test the hypothesis (**H2**) that humpback chub growth in terms of length and weight are asynchronous due to asynchrony in the CRe between temperature and food availability. Resolving H1 and H2, will help to place negative effects of rainbow trout on humpback chub in their proper context. This will allow us to better address two central management questions in the CRe; 1) to what degree is management of rainbow trout through trout management flows or mechanical removal necessary to maintain a healthy humpback chub population; and 2) can flows or other dam management be used to improve the overall health of the ecosystem?

While primarily designed to inform questions about juvenile humpback chub in the mainstem Colorado River, the JCM study is also a mark-recapture study of larger size classes of humpback chub and provides data used to estimate on triggering variables associated with the BiOp, as well as some of the data necessary to estimate total adult abundance. In addition, the JCM study includes invertebrate drift sampling (Project F) and is the only project currently weighing humpback chub, which allows for estimates of fish condition in the Colorado River. The information from these additional components played an essential role in guiding the response of scientists studying humpback chub, when LCR sampling in spring of 2015 indicated a decline in the abundance of spawning adults of ~40% from the prior year. A decline of this degree is difficult to reconcile with our understanding of adult humpback chub survival, as well as our expectation of continuing recruitment from sub-adult size classes (to be clear we expected rainbow trout to have lowered this rate, but not to zero). Initially, we wondered if the migration had been early and had been missed by sampling. However, data from the LCR passive integrated transponder (PIT)-tag antenna array indicated that the timing of the spawning migration was the same as the year prior. Fortunately, we knew from invertebrate drift sampling that there was far less food available in 2014 than in years prior, and that adult humpback chub condition factor had declined over this period. This information, together with our knowledge that humpback chub exhibit skip-spawning (i.e., only some percentage of adults spawn each year; Yackulic and others, 2014) and that skipped-spawning in many fish species increases when insufficient food is available (Rideout and Tomkiewicz, 2011), led us to urge caution in interpreting a decline in spawning adults as a decline in the adult population.

Specifically, we argued that the hypothesis (H3) that humpback chub are in poor condition and are spawning at a lower rate than in prior years was better supported by available data, then the alternative hypothesis (H4) that there had been a massive decline in the adult humpback chub population. Such a decline in adult survival could hypothetically have occurred in the mainstem (H4a) or in the LCR (H4b). The hypothesis (H4b) that humpback chub in the LCR had decreased survival during the fall of 2014 was based on observations of multiple fish species having difficulty breathing during a flood with unusually high sediment loads. The number of adult spawners remained low in 2016; however, condition factor of adult humpback chub in the Colorado River remained low and integrated modeling of data from the mark-recapture studies in the LCR and JCM via a multistate model (Yackulic and others, 2014) continues to support the hypothesis of reduced humpback chub spawning rate (H3) over the hypothesis of a decline in adult humpback chub survival (H4a, b). However, since we have extremely low capture probabilities in the Colorado River, we cannot entirely rule out H4 yet. Furthermore, the uncertainty in estimates of adult abundances has increased substantially over the last two years. Even if reduced food availability has not decreased adult humpback chub survival yet, it is possible that continuation of low invertebrate drift densities (see Project F) will eventually lead to declines in survival and/or decreased recruitment from smaller size classes. For these reasons, we see understanding the drivers of recent declines in the aquatic food base (both the role of nutrients, Project E, and the role of flows, Project F) as essential research alongside ongoing monitoring in the JCM program.

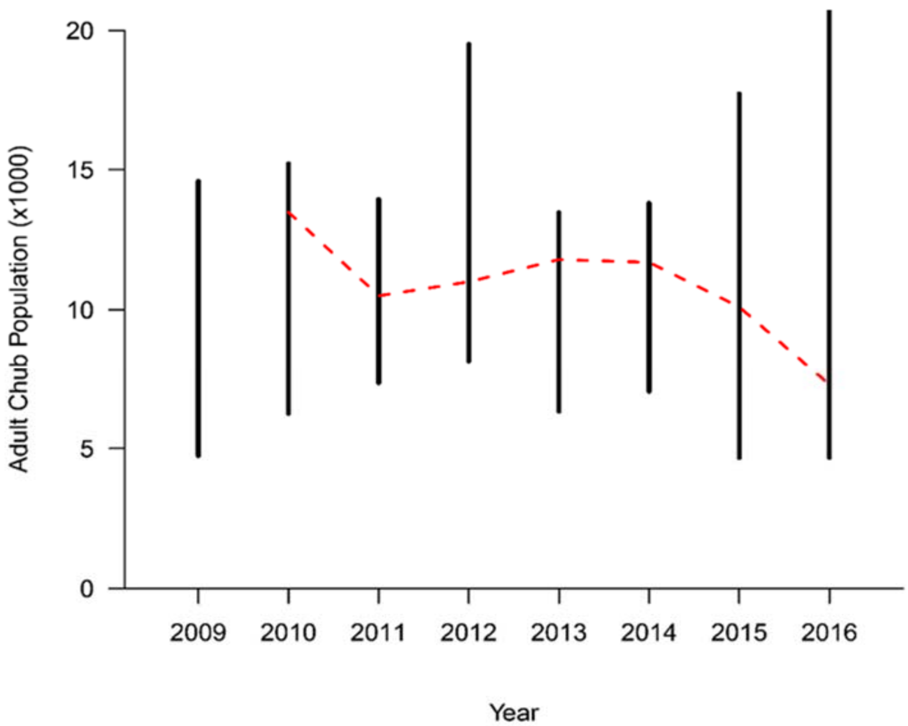

Figure 1. Adult humpback chub abundance estimates (95% Confidence intervals in black) based on a multistate mark-recapture model that allows for skip-spawning, variation in skip-spawning in different year, and differential growth rates in the Little Colorado River (LCR) and Colorado River. The rate of spawning for both smaller (200-250 mm) and larger (250+ mm) humpback chub adults has declined by approximately 50% in 2015 and 2016 leading to greater uncertainty in population abundances. Given the choice, however, the model prefers the hypothesis of a decline in spawning over the hypothesis that adult survival has declined. A model that used only LCR data and assumed fish present in the LCR were a random sample of the population (assumptions that are now known to be grossly violated) would wrongly attribute the decline in spawning rate to a decline in adult survival and suggest a 40% decline in adult abundances over the last two years (red line).

Importantly, if only information from the LCR monitoring had been available in 2014 and 2015, and populations had been assumed to be well-mixed (i.e., the assumptions outlined above), we might now believe that were in the midst of a substantial decline (red line in Fig. 1) and would have no evidence suggesting a declining aquatic food base in the mainstem. In fact, it seems plausible that, in the absence of information collected by the JCM program, humpback chub decline was due to the large number of rainbow trout produced during the period 2008-2012. The implication of this is that the AMP needed to focus on removing non-natives near the LCR, rather than on better determining the effects and drivers of declining invertebrate production.

Humpback chub that do not spawn in the LCR

Available data suggest that 2014 was a tale of two rivers. In Glen and Marble Canyons, both primary production and invertebrate drift were declining (potentially due to declining SRP;

Project E), leading to both declining condition in adult humpback chub and declining condition and abundances of juvenile humpback chub. In contrast, in the Grand Canyon reaches of the CRe, there was evidence of higher levels of juvenile humpback chub recruitment than had previously been observed (Young, pers. obs.). Temperatures at National Canyon (RM 167) and Diamond Creek (RM 225) in 2014 were comparable to temperatures observed in these locations during 2000 and 2005, the two other warmest years in the last twenty years, and it has long been hypothesized that cold temperatures alone limit humpback chub recruitment. This untested hypothesis formed the basis for assessing effects of management alternative on humpback chub aggregations, excluding the LCR aggregation, during the LTEMP process via a temperature suitability modeling. Flows, nutrients, food, and interspecific interactions were assumed to be unimportant as factors affecting humpback chub population dynamics. While there have been no hypothesis-driven studies of humpback chub population dynamics outside of the LCR to test these assumptions, available evidence from the LCR suggests that drivers are often more complicated.

The hypothesis that temperature alone limits humpback chub recovery downriver of the LCR (and by proxy that the abundance of food matters near the LCR, but does not matter further downriver) is questionable given that warmer temperatures almost always increase metabolism and thus food requirements. We can think of at least four hypotheses to explain the "two rivers" contrast in 2014. Some of these hypotheses will be addressed through this project, and others which will be addressed more directly through Projects E and F. The first hypothesis (H5) is that humpback chub densities are still so low in the lower half of the river that food limitation is not yet an important factor, but will become one if populations continue to recover – with implications for establishing a second population. The next hypothesis (H6) is that humpback chub in the lower half of the river are not as dependent on autochthonous production (i.e., diatoms in the river that require SRP and that in turn are the main food of the aquatic insects on which humpback chub feed), and thus are less affected by the amount of SRP in dam releases (see Project E). Alternatively, since we know very little about nutrients downstream of Lees Ferry, we might hypothesize (H7) that there were sources of SRP downstream of the LCR in 2014, such that autochthonous production did not decline as substantially in the lower half of the Colorado River as they did in Glen and Marble Canyons. There are myriad processes (tributary inflows, nutrient spiraling, etc.) that could explain such a spatial difference in SRP availability (see Project E). In particular, a final hypothesis (H8) is that frequent HFEs over the last four years have exported large quantities of aquatic vegetation biomass (including a big pool of phosphorous within that biomass) and mineral phosphorus in sediment from the upper part of the CRe, into the lower part, providing a slow drip of SRP to the downriver ecosystem. Work in the 1990s suggested that HFEs can play an important role in establishing sand deposits as phosphorous hotspots (Parnell and others, 1999).

Distinguishing among these hypotheses to determine drivers of these humpback chub populations is difficult, in part, because there are no ongoing intensive studies of the food base, humpback chub, or other fish species in the lower half of the Colorado River. However, determining if the drivers of population dynamics near the LCR and in the western portions of the Grand Canyon are the same is vital for understanding the long-term viability of humpback chub downstream of GCD. Knowing what the drivers of population dynamics in the lower half of the CRe are, and whether dynamics in this portion of the Colorado River and the near the LCR are synchronous is arguably more important to overall extinction risk than knowing the amount of genetic exchange between the subpopulations near the LCR and in western Grand Canyon. Consideration of two scenarios illustrates this point. In scenario A, the two populations have minimal exchange of individuals, but are highly synchronous (i.e., they decline and increase together), so the second population adds little demographic redundancy or resilience. In scenario B, exchange is more frequent, but subpopulation dynamics are highly asynchronous leading to an overall population with a much higher probability of long-term persistence with implications for down-listing of humpback chub. For these reasons, we propose establishment of a fixed juvenile chub study area in western Grand Canyon (JCM-west), using similar methodologies as the JCM near the LCR, to better understand the drivers of humpback chub populations at downstream locations.

This approach will provide novel insights with applicability throughout the lower half of the Grand Canyon, because, while monitoring via the aggregation sampling project provides length-frequency and catch statistics at a number of sites (Persons and others, 2017), it does not have the statistical power to detect different trends in different sites, cannot estimate absolute abundances, and is an inefficient sampling scheme for learning about drivers and testing hypotheses like H5-H8. JCM-west is the approach best suited for addressing conservation measures in the BiOp calling for a better understanding of drivers and estimates of abundances for aggregations other than the LCR. If estimates of capture probabilities in this western JCM are comparable to estimates for the LCR-JCM study, or if differences can be explained statistically by including environmental covariates in the analysis, we may be able to develop statistical models to provide rigorous estimates of abundances at other aggregations. Importantly, sampling in the Colorado River near the LCR as part of the JCM study and its precursor, the near shore ecology project, has shown us that at least six days of sampling at a location using multiple gear types are required to accurately estimate capture probabilities (and resulting abundances) so it is not surprising that two-day sampling events using only hoopnets as part of the aggregation study did not lead to usable abundance estimates.

Translocated humpback chub

Translocations are an important management tool recognized by the LTEMP and BiOp as a key component of humpback chub management and a potential means to avoid mechanical removal of trout in the mainstem Colorado River near its confluence with the LCR. The 2016 PEP panel on fisheries indicated there was a need to make the translocation program more rigorous quantitatively, to identify goals, and to design translocations to address key uncertainties about the effectiveness of this management action. There is clear evidence that humpback chub translocated upstream of Chute Falls grow much more quickly and likely survive at higher rates, suggesting a benefit to humpback chub. At the same time, the Chute Falls translocation effort does not provide much additional redundancy to the humpback chub population. If something catastrophic happens to the LCR population downstream of Chute Falls, it will also likely negative effect the population upstream of Chute Falls. Further, the translocation process involves costs such as potential handling mortality. These downsides to the Chute Falls translocation effort suggest a need to not just show that growth and survival rates are greater upstream of Chute Falls, but to make a counter-factual comparison to test the hypothesis (H9) that the Chute Falls translocation is adding a sufficient number of adults to the population to justify the costs. We plan to test H9 through a joint analysis by GCMRC and USFWS scientists. Dependent on the results of this analysis, USFWS will reconsider the need for continuation of Chute Falls translocation, including the conditions (e.g., overall adult chub abundances) under which this management action is most useful.

Translocations into Havasu Creek are intended to establish a secondary reproducing population, adding demographic redundancy for humpback chub and meeting downlisting or delisting criteria specified in Recovery Goals. While there is compelling evidence that this effort is succeeding, there is also concern that the amount of habitat currently available for humpback chub in Havasu Creek is insufficient to maintain a self-sustaining population, and the BiOp identifies the need to consider translocations further upstream in Havasu Creek. During this work plan, we plan a feasibility study to be led by USFWS, pending approval by the Havasupai Tribe. If approved, this effort could be used to test various hypotheses about the most effective approaches to translocation (juveniles vs. ripe adults, hard vs. soft releases, timing, etc.).

5. Proposed Work

5.1. Project Elements

Project Element G.1. Humpback chub population modeling

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project are to provide better tools to understand the current state of the humpback chub resource (e.g., adult population size) and to predict its future state in response to management decisions. Estimates from the multistate model can be used to populate a matrix population model based on the same states allowing for easy translation from estimation to prediction (see modeling to support the LTEMP EIS). During the FY2015-17 work plan, our work focused on: 1) examining drivers of growth in the Colorado River and LCR (Dzul and others, 2016), 2) development of mark-recapture models to jointly model the dynamics of rainbow trout and humpback chub populations, allowing us to test hypotheses about environmental conditions versus interspecific interactions (Yackulic and others, *in press*), 3) using data from the LCR PIT-tag antenna array to quantify the flux of rainbow trout that move into the LCR every winter (Dzul and others, *in press*), 4) aiding in analysis of age 0 and age 1 humpback chub abundances in the LCR over the last 15 years (Van Haverbeke and others, *in prep*.), and 5) collaborating with GCMRC's economist to develop decision support tools from humpback chub and rainbow trout population models (Project J). In addition, we provide annual estimates of humpback chub abundances for BiOp triggers and helped interpret the recent decline in spring spawner abundance.

In FY18-20, we plan to: 1) incorporate fish translocated upstream of Chute Falls into population models to assess translocation effectiveness, addressing H9; 2) develop new models to understand how food availability, intraspecific densities, and the asynchrony between food availability and temperatures in the CRe interact to affect humpback chub survival, growth and spawning probability, as well as to better understand current trends in adult abundance, addressing H1 – H4 (this project element may also address H5-8 using data from the JCM-West project); and 3) integrate new forms of portable remote antenna data (including shore-based single antennas in the LCR, and portable remote antennas in the Colorado River) into our population models, helping to address H3 and H4.

Project Element G.2. Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR

Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office
Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Estimating the abundance of humpback chub adults that spawn in the LCR requires sampling in both the CRe and LCR. Sampling in the LCR during the spring along the lower 13.6 km of the LCR is the best opportunity to mark and recapture adults in the system as those adults that are present have much higher capture probabilities in the LCR than when they are in the mainstem. On the other hand, it is the adults captured during the fall that directly inform overall adult abundance estimates for the population as the overall precision in adult abundances is lowest in this time period (uncertainty in total adult abundances is determined primarily by uncertainty in mainstem abundances, not LCR abundances). Data collected during these trips are all used to estimate spring and fall closed population abundance for various size classes of humpback chub (e.g., 100-149 mm, 150-199 mm, > 150 mm, and > 200 mm total length), and during some years provides abundance estimates of other native fishes (Van Haverbeke, 2013). Specific objectives for FY2018-20 (similar to objectives for previous years) are:

1) Determine length stratified estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm) in the lower 13.6 km of the LCR during the spring and fall.

2) Generate a population estimate of age 0 humpback chub (40-99 mm) during fall after some variable proportion of age 0 humpback chub have emigrated to the mainstem.
3) Collect data on PIT-tagged fish in support of humpback chub population modeling.
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 element from previous years include continued collaboration with fish biologists from the Navajo Nation, expansion of remote sensing efforts throughout the LCR, and exploration of changes to sampling methods (e.g., extra gear types) that could eventually lead to a single fall trip in future years (in addition to maintaining two spring trips).

Project Element G.3. Juvenile chub monitoring near the LCR confluence

Mike Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element provides the data to estimate survival, growth and abundance of multiple size classes of humpback chub in the mainstem Colorado River just downstream of the LCR confluence. During FY2018-20, we propose three trips a year (April, June/July and October), down from four trips in prior years. These trip times were chosen based on species life history and to maximize the cost-effectiveness of this project. Trips will use a variety of gear types to sample fish (e.g., hoopnets, portable remote antennas, nighttime electrofishing). The multistate model used to estimate total adult abundances requires data from this project, and total adult abundances are required for triggers associated with the BiOp. This project also allows us to estimate rainbow trout and brown trout abundance in this same reach and we plan to use these data, along with data from Lees Ferry, to continue to track the relationship between rainbow trout production in Lees Ferry and rainbow trout abundances near the LCR. Invertebrate drift and fish weights were also collected as part of this project and provided invaluable secondary information for interpreting the decline in spawner abundance in 2015 and 2016 as being caused by declining fish condition due to decreased food availability.

This project element also includes pre-monsoon sampling in the LCR to better understand variation in juvenile production and outmigration – key vital rates that are important for understanding whether pre-emptive rainbow trout management via trout management flows or mechanical removal is needed to meet population targets (Yackulic and others, *in press*). Recaptures of visual implant elastomer (VIE)-marked humpback chub in the CRe, especially humpback chub marked through the June-July LCR sampling are crucial to understanding annual survival and movement out of the LCR into the Colorado River. In FY2018-20, we will increase our use of remote antennas (successfully piloted in the September 2016 JCM trip), which can be used to noninvasively sample previously tagged fish, and can be placed in locations where adult fish are more likely to congregate and are difficult to sample through other means.

Project Element G.4. Remote PIT tag array monitoring in the LCR

Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office
Bill Kendall, U.S. Geological Survey, Colorado State University
Dana Winkelman, U.S. Geological Survey, Colorado State University
Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project are to provide data to track the timing of the annual humpback chub spawn, test hypotheses about trap avoidance, and inform our population model. The antennas read and record PIT-tag codes from marked fish along with a date and time for each reading as tagged fish pass near antennas anchored to the river bottom or river bank. The value of this form of monitoring was clear in 2015, when we were able to rule out the hypothesis that decreased spawning abundance was due to sampling having missed the actual spawn. Starting in spring 2017, we are piloting shore-based antennas placed at natural pinch points in the LCR as an alternative to the current cross channel PIT-tag antenna arrays. The antennas are less expensive and we are optimistic they will provide as good or better data. During the pilot study we have placed six single antennas in the river at strategic locations (as compared to the 12 antennas used in the current arrays), and we are planning power analyses to determine whether we can use fewer antennas (e.g., three or four).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 and in FY2018-20, we will be developing population models that more fully incorporate the data provided by these antennas.

Project Element G.5. Monitoring humpback chub aggregation relative abundance and distribution

Kirk L. Young, Fish Biologist, U.S. Fish and Wildlife Service
Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service
Michael Dodrill, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Brian Healy, Fish Biologist, National Park Service, Grand Canyon National Park

Aggregations of humpback chub in Grand Canyon are biologically important because they potentially provide redundancy and resiliency for the species. Annually monitoring of the status and trends of humpback chub aggregations and conducting periodic surveys in between aggregations to identify additional aggregations and individual humpback chub are Conservation Measures listed in the BiOp. This project will conduct one mainstem sampling trip per year focused on aggregations and one additional mainstem sampling trip in 2019 focused on areas between aggregations. The annual aggregations trip will focus on hoop net monitoring the known aggregations (e.g., RM 30-36, LCR, Bright Angel, Shinumo, Stephens Aisle/Middle Granite Gorge, Havasu, Pumpkin Springs). The primary objective of this annual trip will be to continue a long-term catch per unit (CPUE) index that has been constructed since the early 1990s (Persons and others, 2017). Portable PIT-tag antennas will also be utilized to detect tagged fish, providing additional information on humpback chub, while reducing handling of fish.

Project Element G.6. Juvenile chub monitoring—West

Mike Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

In recent years, catch in humpback chub aggregations in the western Grand Canyon have increased dramatically, but current sampling is insufficient to determine drivers. This project is designed to gain a better understanding of drivers of population dynamics, as well as environmental factors that drive variation in capture probabilities. Understanding the drivers of, and developing rigorous population estimates for, aggregations outside the LCR are identified as Conservation Measures in the BiOp. Furthermore, the 2016 fisheries PEP specifically recommended additional study in the lower part of the CRe. If drivers are significantly different in the lower part of the river, this may provide redundancy as dynamics will be asynchronous. Furthermore, many of our a priori hypotheses (H5-H8) about why dynamics could be different in the lower part of the CRe have significant implications for dam management. One lesson from the nearshore ecology study (the precursor to the JCM project) is that six or more days of sampling are required to estimate capture probabilities (and abundance) for humpback chub. In 2017, we are planning a pilot study to determine the best location for JCM-West with three potential sites currently being considered (Havasu: RM 158-167, Parashant: RM 198-205, and Pumpkin Spring: RM 210-217). Sampling will occur during the same trips as JCM (April, June/July, and October) and use the same sampling methods (with the addition of seining) as are currently employed as part of the JCM project. During 2018, we will visit the same site in each of three trips and then assess results from this project to determine how to proceed in 2019 and 2020.

Project Element G.7. Chute Falls translocations

Kirk Young, Fish Biologist, U.S Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Translocation and monitoring of humpback chub upstream of Chute Falls has been in place as a conservation action in BiOps since 2002 (USFWS 2002, 2011, 2016). We propose to continue translocating juvenile humpback chub to upstream of Chute Falls on an annual basis and to continue annually monitoring them. To date, approximately 3,106 juvenile humpback chub have been translocated upstream of Chute Falls. In conjunction with translocation activities of humpback chub upstream of Chute Falls, we work collaboratively with Southwest Native Aquatic Resources and Recovery Center at Dexter, NM to maintain a long term genetic refuge of humpback chub, and work collaboratively with NPS to provide juvenile humpback chub for translocation activities into Shinumo Creek and Havasu Creek.

Project Element G.8. Havasupai translocation feasibility

Kirk Young, Fish Biologist, U.S Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

We propose to first coordinate with the Havasupai Nation about the concept of translocating humpback chub to upstream of Beaver Falls in Havasu Creek. If the Havasupai Nation is supportive, we will work with the tribe to implement surveys and develop feasibility and objective-driven action plans. This project is listed as a conservation action in the LTEMP BiOp (U.S. Fish and Wildlife Service, 2016).

Project Element G.9. Backwater seining

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A potentially useful monitoring tool for long-term assessment of native and nonnative fish populations would be to develop a better understanding of backwater catch rates as an index of population size (Dodrill and others 2015). Juvenile native fish, including humpback chub, often occur in backwaters at high densities, yet this type of habitat represent a small proportion (<1%) of the total amount of available habitat used by native fish. Although differences in the abundance of native fish populations have not been reliant on the occurrence of backwaters, this type of habitat often affords researchers with an effective means to assess fish populations, particularly for the reason that backwaters have high fish densities per amount of sampling effort compared with other habitat types sampled (Hoffnagle 1996; Dodrill and others 2015). One of the objectives of this project will be to continue on with the long-term assessment of juvenile native and nonnative fishes, which include metrics such as CPUE, species composition, and size distributions, as well as the spatial distribution of these habitats. The key objective of this project is to develop a relationship between fish abundance estimates and catch rate indices with backwaters, and determine how these two metrics vary with environmental factors that drive differences in capture probabilities. Capture probabilities for backwaters are known to be highly variable and, depending on the method used for determining abundance, are likely to create sampling biases. Backwater abundance estimates are to be determined using two methods (seine-depletion and mark-recapture). These data, and the resulting relationships will help inform past efforts to monitor backwaters (2002-2016), as well as other project elements including the JCM-LCR (G.3) and JCM-West (G.6) projects. This project will conduct one mainstem sampling trip per year that is scheduled for August, and will address the study hypotheses identified as H5-H8.

5.2. Deliverables

The work described here will lead to multiple peer-reviewed publications (e.g., research from similar projects in the last TWP led to eight manuscripts that have been published or are in press). We will provide annual summaries of state variables and vital rates relevant to the BiOp (e.g., abundance, survival, recruitment, and growth rates) at the Annual Reporting Meeting each January. Also, we will provide more frequent summaries of some monitoring metrics to the TWG and stakeholder groups if there is additional interest in further evaluating the response of humpback chub to any combination of LTEMP flow experiments.

6. References

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—An update considering data from 1989-2008: U.S. Geological Survey Open-File Report 2009-1075, 18 p., http://pubs.usgs.gov/of/2009/1075/.

Coggins, L.G., Jr., Pine, W.E., III, Walters, C.J., Van Haverbeke, D.R., Ward, D., and Johnstone, H.C., 2006, Abundance trends and status of the Little Colorado River population of humpback chub: North American Journal of Fisheries Management, v. 26, no. 1, p. 233-245, http://dx.doi.org/10.1577/M05-075.1.

Dodrill, M.J., Yackulic, C.B., Gerig, B., and Finch, C., 2014, 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, v. 31, no. 10, p. 1203-1217, http://dx.doi.org/10.1002/rra.2842.

Dzul, M.C., Yackulic, C.B., and Korman, J., 2017 *in press*, Estimating animal abundance using continuous detection data from PIT arrays placed near the confluence of two rivers: submitted to Canadian Journal of Fisheries and Aquatic Sciences, USGS approved.

Dzul, M.C., Yackulic, C.B., Korman, J., Yard, M.D., and Muehlbauer, J.D., 2016, Incorporating temporal heterogeneity in environmental conditions into a somatic growth model: Canadian Journal of Fisheries and Aquatic Sciences, v. 74, no. 3, doi: 10.1139/cjfas-2016-0056, p. 316-326, http://dx.doi.org/10.1139/cjfas-2016-0056.

Hasler, A.D., Scholz, A.T., and Goy, R.W., 1983, Olfactory imprinting and homing in salmon—Investigations into the mechanism of the imprinting process, v. 14, Zoophysiology: Berlin, Heidelberg, New York, Tokyo, Springer-Verlag.

Irving, D.B., and Modde, T., 2000, Home-range fidelity and use of historic habitat by adult Colorado pikeminnow (*Ptychocheilus lucius*) in the White River, Colorado and Utah: Western North American Naturalist, v. 60, no. 1, article 2, p. 16-25, http://scholarsarchive.byu.edu/wnan/vol60/iss1/2.

Kendall, W.L., Nichols, J.D., and Hines, J.E., 1997, Estimating temporary emigration using capture–recapture data with Pollock's robust design: Ecology, v. 78, no. 2, p. 563-578, http://dx.doi.org/10.1890/0012-9658(1997)078[0563:ETEUCR]2.0.CO;2.

Morin, P.-P., Dodson, J.J., and Doré, F.Y., 1989, Cardiac responses to a natural odorant as evidence of a sensitive period for olfactory imprinting in young Atlantic salmon, *Salmo salar*: Canadian Journal of Fisheries and Aquatic Sciences, v. 46, no. 1, p. 122-130, http://dx.doi.org/10.1139/f89-016.

Parnell, R.A., Jr., Bennet, J.B., and Stevens, L.E., 1999, Mineralization of riparian vegetation buried by the 1996 controlled flood, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 225-239.

Pearson, K.N., Kendall, W.L., Winkelman, D.L., and Persons, W.R., 2015, Evidence for skipped spawning in a potamodromous cyprinid, humpback chub (*Gila cypha*), with implications for demographic parameter estimates: Fisheries Research, v. 170, p. 50-59, https://doi.org/10.1016/j.fishres.2015.05.015.

Persons, W.R., Van Haverbeke, D.R., and Dodrill, M.J., 2017, Colorado River fish monitoring in Grand Canyon, Arizona—2002–14 humpback chub aggregations: U.S. Geological Survey Open-File Report 2016-1177, 43 p., https://doi.org/10.3133/ofr20161177.

Rideout, R.M., and Tomkiewicz, J., 2011, Skipped spawning in fishes—More common than you might think: Marine and Coastal Fisheries, v. 3, no. 1, p. 176-189, http://dx.doi.org/10.1080/19425120.2011.556943.

Scholz, A.T., White, R.J., Horton, S.A., and Koehler, V.A., 1991, Measurement of egg and larval thyroxine concentration as an indicator of the critical period for imprinting in razorback suckers (*Xyruachen Texanus* (Abbott))—Implications for recovery of endangered stocks in the Colorado River Basin: Cheney, Wash., Eastern Washington University, Department of Biology, Colorado River Endangered Fisheries Project, technical report no.1, submitted to Bureau of Reclamation, 26 p., http://www.nativefishlab.net/library/textpdf/20597.pdf.

Van Haverbeke, D.R., Stone, D.M., Coggins, L.G., and Pillow, M.J., 2013, Long-term monitoring of an endangered desert fish and factors influencing population dynamics: Journal of Fish and Wildlife Management, v. 4, no. 1, p. 163-177, http://dx.doi.org/10.3996/082012-JFWM-071.

Yackulic, C.B., Korman, J., Yard, M., and Dzul, M.C., 2017 *in press*, Inferring species interactions through joint mark-recapture analysis: submitted to Ecology, USGS approved.

Yackulic, C.B., Yard, M.D., Korman, J., and Van Haverbeke, D.R., 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, v. 4, no. 7, p. 1006-1018, http://dx.doi.org/10.1002/ece3.990.

7. Budget

		Fiscal Year 2018							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***								
G.1	Humpback chub population modeling	$78,290	$2,000	$3,000				$12,957	$96,247
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$7,201		$8,500	$88,080	$337,506		$26,270	$467,557
G.3	Juvenile chub monitoring near the LCR confluence	$138,763		$17,000	$139,500			$45,934	$341,197
G.4	Remote PIT tag array monitoring in the LCR	$37,395		$3,500	$6,000			$7,295	$54,190
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$22,258		$8,000	$42,616	$84,240		$13,864	$170,978
G.6	Juvenile chub monitoring – West	$85,857		$12,000	$114,500			$33,036	$245,393
G.7	Chute Falls translocations	$6,890		$3,000	$8,000	$65,520		$4,749	$88,159
G.8	Havasupai translocation feasibility							$0	$0
G.9	Backwater Seining	$20,669		$5,000	$11,000			$5,705	$42,374
	Total G	**$397,323**	**$2,000**	**$60,000**	**$409,696**	**$487,266**	**$0**	**$149,811**	**$1,506,095**

		Fiscal Year 2019							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***								
G.1	Humpback chub population modeling	$75,161	$2,000	$3,000				$20,842	$101,003
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$8,194		$8,500	$91,200	$337,506		$38,178	$483,578
G.3	Juvenile chub monitoring near the LCR confluence	$139,356		$17,000	$150,000			$79,653	$386,009
G.4	Remote PIT tag array monitoring in the LCR	$38,517		$6,000	$6,000			$13,134	$63,651
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$32,817		$10,500	$88,468	$84,240		$36,791	$252,816
G.6	Juvenile chub monitoring – West	$61,459		$12,000	$125,000			$51,599	$250,058
G.7	Chute Falls translocations	$9,582		$3,000	$8,000	$65,520		$7,317	$93,419
G.8	Havasupai translocation feasibility							$0	$0
G.9	Backwater Seining	$21,289		$2,000	$11,500			$9,045	$43,834
	Total G	**$386,374**	**$2,000**	**$62,000**	**$480,168**	**$487,266**	**$0**	**$256,559**	**$1,674,368**

		Fiscal Year 2020							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***								
G.1	Humpback chub population modeling	$83,058	$2,000	$3,000				$22,895	$110,953
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$13,818		$8,500	$93,800	$337,506		$40,316	$493,941
G.3	Juvenile chub monitoring near the LCR confluence	$143,537		$17,000	$153,000			$81,520	$395,057
G.4	Remote PIT tag array monitoring in the LCR	$39,672		$6,000	$6,000			$13,435	$65,107
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$28,619		$10,500	$47,948	$84,240		$25,165	$196,472
G.6	Juvenile chub monitoring – West	$63,303		$12,000	$128,000			$52,859	$256,162
G.7	Chute Falls translocations	$9,870		$3,000	$8,000	$65,520		$7,392	$93,782
G.8	Havasupai translocation feasibility				$8,000	$14,400		$2,512	$24,912
G.9	Backwater Seining	$21,928		$2,000	$12,000			$9,341	$45,269
	Total G	**$403,804**	**$2,000**	**$62,000**	**$456,748**	**$501,666**	**$0**	**$255,433**	**$1,681,653**

8. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element G.(i). Imprinting study

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Mainstem translocations are identified as a management tool in the LTEMP EIS and BiOp, with the goal of establishing and/or augmenting reproducing populations in the mainstem CRe. Establishment of new reproducing populations within the mainstem CRe may also enable the CRe population of the humpback chub to meet downlisting or delisting criteria (2002 Humpback Chub Recovery Goals). Resolution of hypotheses H5-H8 regarding whether there is sufficient food for more humpback chub (is it merely temperature that limits mainstem populations in the lower half of the CRe) clearly will inform the use of this tool. However, there are additional, untested hypotheses underlying application of mainstem translocation. For example, the hypothesis (H10) that humpback chub imprint on a spawning area when they are a few days old would suggest that fish artificially translocated to the mainstem CRe may still travel back to the LCR for spawning purposes, even if they otherwise remain far downriver at other times. Translocated individuals that return to spawn in the LCR but do not otherwise remain there could potentially add some demographic redundancy to the CRe humpback chub population overall, in the sense that individuals would experience different conditions and different drivers if they mainly live downriver. However, it would clearly be preferable to have reproduction occurring in places other than the LCR from a recovery perspective. Translocating ripe adults and having them spawn (as opposed to translocating juveniles) might be a reasonable alternative approach if H10 is supported. Importantly, if olfactory cues are important in guiding humpback chub to spawning sites, humpback chub translocated to the mainstem downstream of the LCR would be more likely to return to the LCR than would humpback chub translocated to tributaries: Compared to humpback chub adults in tributaries downstream from the LCR, humpback chub in the mainstem would be more likely to encounter olfactory cues that might trigger them to move upstream into the LCR when they reached reproductive maturity.

The objective of this project element is to assess whether thyroid induced olfactory imprinting occurs in humpback chub and if it does occur, determine the timing of imprinting. This information can then be utilized to make existing translocation efforts more effective. If humpback chub imprint on chemical cues of their natal stream as larvae then translocated fish may not remain where they are placed once they reach reproductive maturity. Many of these fish may instead attempt to return to the LCR to spawn, thereby reducing the likelihood of establishing additional spawning populations and meeting downlisting or delisting criteria. It is therefore critical to understand if humpback chub imprint on their natal stream of origin as larval fish. Other native fishes of the Colorado River such as the Colorado pikeminnow (*Ptychocheilus* *lucius*) and razorback sucker imprint on chemical cues at natal spawning areas and return to those areas as adults to spawn ((Irving and Modde, 2000; Scholz and others, 1991). Surges in thyroid hormones have been shown to be good indicators of imprinting in a variety of fish species (Hasler and Scholz, 1983; Morin and others, 1989). We propose to determine if humpback chub experience thyroid-induced olfactory imprinting by measuring levels of the hormone thyroxine (T4) in developing humpback chub eggs and larvae obtained from captive reared hatchery specimens. Understanding imprinting in humpback chub will help managers to determine the metapopulation dynamics of humpback chub in Grand Canyon and may help to explain why the LCR is the only place in Grand Canyon where larval and juvenile humpback chub are consistently found. Eggs and larvae will be collected at daily intervals from the date of fertilization until 20 days post-fertilization and then at 7-day intervals until 70 days post fertilization. Three samples containing 10 eggs or larvae will be collected at each interval. Mean T4 concentration of each sample of eggs or larvae will be assayed to determine when T4 levels peak as an indicator of time of imprinting. Thyroxine will be extracted from eggs using methods described in (Scholz and others, 1991) where eggs or larvae are minced, mixed with ice-cold ethanol, homogenized, centrifuged and frozen at -80 °C until T4 can be extracted and concentrated using radioimmunoassay. Samples will be assayed for T4 content using a Coat-a-Count T4 Radioimunoassay kit (Diagnostic Products Inc.) which utilizes a procedure based on competitive binding. Concentrations of unknown samples will be determined using a gamma counter to compare bound fractions of T4 to a standard curve with known concentrations of T4 subjected to the same assay procedures. These methods will allow researchers to assess whether or not thyroid induced olfactory imprinting is occurring in humpback chub and the timing of imprinting if it does occur.

Project Element G.(ii). Infrared radar cameras

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Handheld forward looking infrared radar (FLIR) cameras will be used to thermally image the Colorado River and identify warm springs within the mainstem that may be correlated with increased humpback chub catch rates. Thermal imaging cameras have been used to map groundwater inputs and temperature distributions in other Arizona streams and have been shown to be effective at identifying and mapping the extent of warm-water springs at RM 30 within Marble Canyon. This relatively low-cost tool will allow identification currently unknown warm water inputs within the Colorado River that may provide important thermal refuges for humpback chub.

Project Element G.(iii). Spatial analysis of ripe fish

To better understand spawning of humpback chub, we will collect from 2000 through the present along with existing high resolution habitat data from the LCR. Our work will also establish a methodology for linking habitat data to existing long-term fish data, which are already maintained by the GCMRC and may be directly applied to other fish species. Understanding the habitat conditions in which ripe humpback chub are typically caught may help us understand why juvenile production varies so much between years (e.g., if pools that are frequently used are filled in with sediment during years of poor production).

Project Element G.(iv). Genetics study

Previous genetic work has suggested that humpback chub downstream from the LCR were clearly connected with the LCR population by gene flow. However, contribution from occasional local reproduction by mainstem aggregations could not be excluded, because sample sizes from each of the aggregations were small. To date, this is the only baseline genetics data that researchers have concerning mainstem aggregations of humpback chub in Grand Canyon. Since this study, annual population has shown that the number of individuals within each aggregation has increased substantially allowing for an opportunity to re-examine population genetics (diversity, population structure, effective size, etc.) among aggregations. An analysis of genetics is currently occurring and if this analysis suggest a need for more work, and if funding is available, we propose additional genetic analysis in FY2018-20.

Project H. Salmonid Research and Monitoring

1. Investigators

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2. Project Summary

Protection of the endangered humpback chub near the LCR is one of the highest priorities of the GCDAMP, but a concurrent priority of the GCDAMP is to maintain a high quality rainbow trout sport fishery upstream of Lees Ferry in Glen Canyon. As such, rainbow trout were an important component in the development of LTEMP (USDOI, 2016b) on GCD operations, and thus were a major consideration in the flow decisions in the selected alternative in the ROD (USDOI, 2016c). Experimental flows proposed in the LTEMP were designed to limit rainbow trout recruitment and dispersal out of Lees Ferry with a goal of maintaining the balance between the sport fishery and the humpback chub population downstream. However, ecosystems are dynamic and there has been a large increase in brown trout recruitment upstream of Lees Ferry over the past few years (Yard, *unpublished data*). Given this new development, it is unclear whether the expansion of brown trout will disrupt the balance between rainbow trout and endangered native fishes downstream, and further, to what degree flow manipulations can be used to manage both species concurrently.

A major component of the proposed study elements herein focus on how experimental flows will influence recruitment, growth, survival, and dispersal of rainbow trout in Glen and Marble Canyons. However, management of the rainbow trout fishery cannot occur in a vacuum given the recent increase in brown trout in Glen Canyon. Small numbers of brown trout have been present in the canyon since the dam was built but have increased following a time period associated with frequent fall-timed HFEs. It is currently unclear whether this relationship is causal or coincidental, but research is needed to examine if the proposed flow manipulations help or hinder the expansion of brown trout. Brown trout are superior competitors in other tailwater systems, are typically not stocked past their initial introduction (Dibble, *unpublished data*), and are known to be voracious predators of small-bodied native fishes (Yard and others, 2011). It is therefore prudent and necessary to not only evaluate the effect of experimental flows on rainbow trout, but also to examine how brown trout populations may respond to such flow manipulations.

This proposal utilizes a combination of field, modeling, and laboratory techniques to evaluate the response of trout to experimental flows including TMFs, HFEs, equalization flows, and macroinvertebrate production flows. Project Element H.1 capitalizes on knowledge gained from the natal origins of rainbow trout (NO) and rainbow trout early life stage studies (RTELSS) projects funded in GCDAMP's FY2013-14 and FY2015-17 work plans. This project proposes a consolidated study design focused on juvenile and adult trout captured during quarterly mark-recapture trips in combination with pre- and post- flow treatments to evaluate early life-history responses to TMFs. This project aims to gain a better understanding of the effects of experimental flows on rainbow trout and brown trout recruitment, growth, survival, dispersal, and movement from GCD to the LCR confluence. Project Element H.2 develops a rainbow trout recruitment and outmigration model that predicts the response of rainbow trout to alternative flows and physical conditions in the CRe. This model can be used to evaluate the ability of alternative monitoring designs to detect rainbow trout responses to LTEMP flow alternatives. Project Element H.3 uses information on vital rates contained within young-of-year (YOY) rainbow trout and brown trout otoliths to improve recruitment models, identify when brown trout are most vulnerable to flow manipulation, and assess the physiological response of brown trout to different types, durations, and timing of experimental flows, which is data that can be used to manage this nonnative species. Finally, Project Element H.4 extends the Arizona Game and Fish Department (AGFD) long-term monitoring of rainbow trout in Lees Ferry and launches a new citizen science program to gather data on angler catch quality in combination with ongoing creel surveys in a cost-effective way. Collectively, these four projects aim to resolve critical uncertainties about the response of rainbow trout and brown trout to experimental flows proposed in the LTEMP that are now the basis for its associated ROD (USDOI, 2016c).

3. Hypotheses and Science Questions

1) What are the effects of TMFs on trout survival, recruitment, growth, and dispersal?
2) What are effects of spring and fall HFEs on trout recruitment, dispersal, and growth?
3) What controls the number of trout that disperse from Glen Canyon into Marble Canyon, and the quantity reaching the LCR?
4) What controls the quality of the trout fishery?
5) What factors regulate brown trout population dynamics in Glen Canyon, and if control measures are implemented, what is the efficacy of those management actions?

4. Background

The LTEMP and ROD identified flow manipulations including TMFs, spring and fall-timed HFEs, macroinvertebrate production flows, and equalization flows as potential policy levers to decrease rainbow trout recruitment (and thereby dispersal) while increasing humpback chub abundance near the LCR (USDOI, 2016b). TMFs were designed to limit rainbow trout recruitment in Glen Canyon with the intent of reducing boom-and-bust cycles in the Lees Ferry fishery and limiting dispersal of rainbow trout from Glen Canyon to the LCR. The ROD also imposed a two-year moratorium on spring-timed HFEs because the 2008 spring HFE appeared to produce a large number of rainbow trout recruits in Glen Canyon (Korman and others, 2011), some of which may have dispersed downstream following this event (Korman and others, 2012). Fall HFEs will likely be the most common experimental flow under the new ROD, but there are concerns from the angling community that these types of experimental floods reduce the aquatic food base during the fall season, a period when trout growth is already low, having negative effects on the population and fishery. Additionally, macroinvertebrate production flows were identified as an alternate flow regime in the ROD that could be used to enhance the aquatic food base and increase growth rates of rainbow trout in Glen Canyon as well as native species downstream.

While the above flows have influenced, or have the potential to influence, rainbow trout recruitment, it is unclear how such flows will influence brown trout populations. Brown trout are associated with a high incidence of piscivory (Yard and others, 2011) and also compete with nonnative and native fish species (Hearn, 1987; Kaspersson and others, 2013), so their recent expansion poses a significant threat to the rainbow trout fishery and likely to endangered humpback chub populations that reside in and near the LCR. In the past, management actions have included labor-intensive mechanical removal of brown trout at the LCR confluence (Mueller, 2005; Coggins and others, 2011) and in Bright Angel Creek (Makinster and others, 2010). However, the high abundance of YOY brown trout in Glen Canyon may require management actions to reduce recruitment before the recruits become reproductively mature adults.

Changes in flow velocity, magnitude, duration, and timing of GCD operations designed in the LTEMP to manage rainbow trout populations may also be used as tools to manage brown trout recruitment and survival since flows can be scheduled to occur when the species is in their most vulnerable life history stage. A recent synthesis of brown trout data from regulated rivers across the western US found that brown trout recruitment is inversely related to flow velocity (Dibble and others, 2015), which may be due to energetic constraints imposed by high flows. Data from other tailwaters indicate that natural flooding events, similar to HFEs released from GCD, can have a significant negative effect on brown trout populations. Winter-timed floods can decrease recruitment by scouring eggs and alevins from gravel redds (Strange and Foin, 1999; Wenger and others, 2011), while spring-timed floods can decrease survival following emergence via energetic constraints (Cattanéo and others, 2002; Budy and others, 2008; Jonsson and Jonsson, 2009). While fall-timed HFEs have occurred concurrently with the increase in brown trout recruitment, there is no causal link between the two phenomena. Therefore it is essential that the influence of different types of flows in the selected alternative be evaluated on behalf of both rainbow trout and brown trout in this current TWP. The project elements proposed herein are driven by five overarching research questions that stem from previous research funded in the FY2013-14 and FY2015-17 GCDAMP work plans. Although the majority of the supporting research for these questions stems from investigations of rainbow trout, the questions apply equally to brown trout.

1) ***What are the effects of TMFs on trout survival, recruitment, growth, and dispersal?***

TMFs are designed to flood and strand YOY trout in low angle shorelines and induce mortality by rapidly dropping water levels. Since it is unclear the extent to which TMFs will reduce recruitment, this project broadly focuses on the following questions: 1) what proportion of total recruits are vulnerable to stranding and mortality in low angle shorelines; 2) what is the relationship between aerial coverage of low angle shoreline and discharge levels; 3) will survival rates of YOY trout increase following a TMF, thereby partially or fully compensating for direct losses of trout during the TMF; and 4) will TMFs unexpectedly trigger a downstream dispersal event? Therefore, we propose to monitor YOY trout survival (Project Element H.1), recruitment (H.1, H.2), growth (H.3), and downstream dispersal (H.1, Project G) in years with and without TMFs to address these critical uncertainties.

2) ***What are effects of spring and fall HFEs on trout recruitment, dispersal, and growth?***

An increase in the growth rate and recruitment of YOY trout in Glen Canyon was observed following the 2008 spring HFE and was attributed to an increase in food availability (Korman and others, 2011). However, it is uncertain whether future spring HFEs will produce a similar response because the 2008 observation was a single, unreplicated event and antecedent conditions at the time of the spring HFE may have been unique (e.g., low trout abundance, higher nutrient availability due to equalization flows). Therefore, if spring HFEs are implemented, we propose to include higher resolution monitoring to detect change in trout populations (Project Element H.1).

The effects of fall HFEs on rainbow trout in Glen Canyon are uncertain even though there have been five fall HFEs conducted to date (2004, 2012–2014, 2016). Mark-recapture data from the NO project clearly shows that fall HFEs do not lead to increased downstream movement (Korman and others, 2015). Additionally, there is some indication that fall HFEs can reduce growth rates of adult trout during late fall and winter in some years (e.g. 2014) but not in others (2016), but results are confounded by strong inter-annual and seasonal variation in growth (Yard and others, 2015). Therefore, additional monitoring of trout growth before and after fall HFEs may resolve uncertainties about their effects on trout growth. Further, evidence indicates fall HFEs reduce adult fish growth during fall and winter, which in turn reduces their rate of sexual maturation and fecundity (Korman and Yard, in review). Therefore, additional monitoring is proposed to examine how adult growth following a fall HFE influences sexual maturation, fecundity, and, by extension, recruitment the following year (Project Element H.1).

3) What controls the number of trout that disperse from Glen Canyon into Marble Canyon, and the quantity reaching the LCR?

The LTEMP model used to simulate rainbow trout movement from GCD to the LCR assumed that trout dispersal was a constant proportion of recruitment, and that trout residency in Marble Canyon was constant through time (USDOI, 2016b). However, NO project data collected from 2011-2016 (which were not available for LTEMP modeling) suggest otherwise. These data indicate that: 1) large numbers of YOY trout disperse from Glen Canyon to the upper and middle portions of Marble Canyon in the summer and fall; 2) trout in Marble Canyon then become the source of trout at the LCR over the next 1-5 years (Korman and others, 2015; Korman and Yard, unpublished data); and 3) prolonged conditions with clear water and high nutrients will maintain large populations of trout in Marble Canyon which in turn will lead to longer periods of high trout abundance at the LCR (Yackulic and others, in review). Therefore, we propose to continue evaluating trout dispersal out of Glen Canyon and monitoring trout population dynamics in Marble Canyon and near the LCR confluence in conjunction with humpback chub monitoring (Project Element H.1, Project G).

4) What controls the quality of the trout fishery?

There is consensus that the quality of the Lees Ferry fishery depends on growth rates of rainbow trout and the number of juvenile trout that recruit into the adult population, which are then targeted by anglers. The LTEMP trout model assumed that fish growth was inversely related to density, and that flow was the only factor that influenced recruitment (USDOI, 2016b). More recent findings indicate that greater food availability during the spring and summer leads to better growth of juvenile rainbow trout and higher recruitment (Korman and others, 2011; Korman and others, 2015; Yackulic, unpublished data). There is also increasing evidence that nutrient availability (specifically SRP) plays an important role in recruitment and adult trout growth by increasing the amount or quality of food. These findings identify deficiencies in the LTEMP trout model because they indicate that: 1) factors other than flow can have important effects on recruitment; and 2) interannual and seasonal variation in nutrients may be a more important determinant on growth than density as assumed in the LTEMP model. Resolving this uncertainty about growth is critical with respect to managing the Lees Ferry fishery. Therefore, we propose to continue studying trout growth and recruitment in relation to both top-down and bottom-up factors such as fish density, nutrient availability, and the prey base to identify key factors that promote a high quality trout fishery in Lees Ferry (Project Elements H.1, H.2, H.3, H.4, Projects F, E).

5) What factors regulate brown trout population dynamics in Glen Canyon, and if control measures are implemented, what is the efficacy of those management actions?

As mentioned above, it is unclear what factors led to the recent increase of brown trout abundance in Lees Ferry, and another unknown is the efficacy of various flow and non-flow control options. Should tagging and release of brown trout be permitted by the NPS, we will estimate state variables and vital rates of this undesirable nonnative fish to help inform future management actions, whether they be flow or non-flow related (Project Element H.1). If managers decide to proceed with a mechanical removal effort, all brown captured from the proposed effort could be removed, which could remove ~18% of the brown trout population each year (Project Element H.1). Removal efforts, if approved, would be coordinated with otolith microstructural analysis to examine hatch and emergence dates to improve experimental flow timing in the future (Project Element H.3). Further, physiological data can be used to gauge the effectiveness of experimental flows on brown trout growth and condition which may, in turn, influence survival and cohort strength the following year (Project Element H.3). Additionally, routine monthly monitoring of nonnative fish by AGFD during the summer and fall (Project Elements I.2 and H.4) will provide a general estimate of population trends using catch per unit effort data. Collectively, the sampling effort proposed herein will improve our understanding of the population dynamics and efficacy of control options for brown trout in Glen Canyon.

5. Proposed Work

5.1. Project Elements

Project Element H.1. Experimental flow assessment of trout recruitment

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The overarching goal of this study element is to determine the effects of LTEMP ROD flows on the recruitment of YOY rainbow and brown trout in Glen Canyon, the growth rate of juveniles and adults, and dispersal of YOY trout from Glen Canyon. Another central objective of this study is to increase our understanding of the key factors (trout density and recruitment, prey availability, nutrients, etc.) that control the abundance and growth of the Glen Canyon trout population. This improved understanding could lead to the identification of policies other than flow manipulation that could benefit the Lees Ferry fishery and limit the downstream dispersal of rainbow trout to the LCR, as well as controlling brown trout should this species become more established in Glen Canyon. Although monitoring programs (e.g., Project Element H.4) are important for documenting long-term population trends and characteristics such as catch-per-unit-effort, size distribution, and occurrence and trends, monitoring as a sole method of data collection is not a very effective approach in time or cost for determining causation, particularly when quantifying and separating out effects from complex interactions that occur among multiple factors (e.g., flow, density, nutrients). In order to study multiple flow treatments and avoid potential confounding factors, we propose to use a seasonal sampling design with spatial replication to determine trout responses to experimental flows and other factors within and across years.

Specifically, the proposed project will evaluate:

1) The effects of higher and potentially more stable flows in spring and summer during equalization events on trout recruitment, growth, and dispersal.
2) The effect of fall HFEs on recruitment of trout in Glen Canyon, measured either through direct effects on juvenile survival or through reduced egg deposition in later years driven by reduced growth of trout (which reduces fecundity and rates of sexual maturation).
3) The effect of spring HFEs on trout recruitment, growth, and dispersal.
4) The effect of TMFs on rainbow and brown trout recruitment and dispersal (contingency plan).

Originally, the proposed project element combined two study components into a single overall project element that evaluated all life stages of trout (rainbow and brown trout) in a consolidated and cost-effective way. These study components included: 1) trout reproductive and growth demographics (TRGD); and 2) trout early life stages (TELS). The second study component, TELS, focused on sampling early life stages of trout in the same three TRGD reaches to understand how flow regimes (described below), in particular TMFs, influenced recruitment. However, some concerns were recently raised during the Budget Ad-hoc meeting (July 19, 2017) about the TELS study component. The central issue was why have in place a sampling design to study effects of TMFs in advance of addressing the questions raised in the LTEMP ROD about experimental flow design (section 2.2.1 Alternative D; LTEMP). Since TMFs are intended to be implemented in the first 5 years of the LTEMP period (if warranted) there are some critical information needs required before TMF implementation, such as: flow duration, magnitude, timing, frequency, and fish responses to antecedent conditions. Recognizing this valid concern, we propose an alternative sampling and modeling approach as part of this project element, which combines both field work (TRGD) and a method for designing an Experimental TMF flow. Subsequently, we have excluded the TELS component from the larger sampling framework

(TRGD). Nonetheless, it remains uncertain whether or not management agencies will still implement a TMF during the FY2018-20; therefore, the TELS component (described below, see *Contingency Plan*) will be executed as a contingency should circumstances arise prior to addressing the LTEMP questions.

The TRGD is similar to the NO of rainbow trout project (FY2015-2017 Work Plan, Project Elements 9.1, 9.2) but reduces costs by decreasing sampling effort and using pre-developed models and analytical approaches (Korman and others, 2017a, 2017b). The modified sampling scheme reduces the temporal and spatial extent of sampling from six trips per year from GCD to Lees Ferry (quarterly with two fall marking trips) to quarterly sampling periods where juvenile and adult trout are sampled every year in three reaches to reduce trip length and cost (i.e., selected reaches consist of both low-angle and high-angle shoreline). The modeling and other analytical approaches for this study component have already been developed which helps avoid costs associated with demographic model development (Korman and others, 2017a, 2017b).

TRGD trout sampling will be conducted in three 3-km reaches in the upper, middle, and lower portions of Glen Canyon using boat-mounted electro-shockers (200–250 V, 20–25 A, pulsed DC). Each of the three reaches contains both low- and high-angle habitats. Each reach will be sampled four times per year in October, January, April, and July, totaling 12 seven-day trips in FY2018-20. The scheduling of these trips will be organized around the timing of anticipated LTEMP flow experiments and in particular fall HFEs, which will be the most common experimental flow. Electrofishing uses state-of-the-art technology to minimize fish injury. The netter captures fish with a long-handled dip net, where fish are then held within aerated 40 liter buckets. These fish are then transferred to a tender boat that transports aerated fish to a central processing location and later returns them to the center point of the original 250 m site of capture after processing. At the central processing location, buckets of incoming fish are kept on the beach and aerated and flushed with water to maintain adequate water quality. These fish are continually monitored for health and condition. Groups of 10–15 fish are anesthetized with clove oil to reduce stress and injury when processed. Fish are removed from anesthetic waters, measured, weighed, and scanned for PIT-tags. Fish remain out of water a minimum amount of time during this processing step. Total time from time of capture to release typically ranges from 1 to 2 hours. We quantify and document all fish mortalities that are associated with monitoring and research activities, regardless of unintentional or intentional take of problematic fish species (Rogers, 2015). Fish handling protocols for GCMRC studies have been in place since the late 1990s (Persons and others, 2015).

Growth between October-January and January-April will represent post-HFE conditions in years when HFEs are conducted, whereas growth over those periods when HFEs are not conducted will form the experimental controls. We will conduct mark-recapture by tagging rainbow trout ≥ 75 mm (fork length) with PIT tags. For the specialized mark-recapture effort (Korman and others, 2016; 2017) we have developed and used a number of other fish handling methods to reduce or entirely avoid unintentional injury or death to fish during the fish sampling and processing effort. These data will be integrated into an open population model to estimate rainbow trout abundance, recruitment, and growth in each reach. Brown trout will also be sampled during quarterly trips; however, estimates of state variables and vital rates will occur only if the tagging and release of brown trout is allowed by the NPS. Some guidance on this issue will likely come from a structured decision making workshop on brown trout, scheduled for September 2017.

The objective of the Experimental TMF component is to develop a conceptual/quantitative model that estimates the optimal flow characteristics to use for stranding juvenile rainbow trout and brown trout. We propose using a combination of analytical methods and field observations to address some of the LTEMP ROD questions (section 2.2.1 Alternative D; LTEMP). The analytical approach proposed will determine: 1) shoreline elevations over a range of flows (5,000 to 25,000 ft^3/s) that maximize vulnerability of juvenile rainbow trout to stranding associated with sudden reductions of flows. We will use stage-discharge relationships in a GIS environment to evaluate the hypsometric characteristics of the shoreline throughout Glen Canyon. This analysis will identify geographical locations and extent of shoreline area having low-angle (less than 11 degree slope) channel margins most sensitive to changes in dam operations. 2) We will evaluate biological data on both trout species, including: a) spatial distribution of spawning bars and age 0 fish densities, b) size-dependent vulnerability based on back-calculated hatch dates for both rainbow trout (Korman and others, 2011; Avery and others, 2015) and brown trout (project H.3). 3) In conjunction with TRGD sampling, other field studies are to be conducted to determine: a) flow duration (time needed to lure fish in along channel margin), b) size-dependent movement rates, and c) size-dependent vulnerability to flow withdrawal rate.

Over the course of the three year work-plan, results from field observations and experiments will be used to develop and parameterize the Experimental TMF model. Once developed, the model will be used to evaluate interactions between physical factors (i.e., flow magnitude, flow duration, ramp rates, seasonal timing) and biological factors (i.e., size-dependent movement rates, size-dependent mortality rates, age 0 fish densities) that effect age 0 stranding. We will explore different tradeoffs that exist between operational constraints (LTEMP ROD), triggering criteria (Project H.2), and early life history information on rainbow trout and brown trout. The model will be used to estimate the most optimal flow characteristics and flow cycles for selecting alternative TMFs to test. This will be followed up by the development of the most appropriate sampling design (e.g., flow titration experiments or block design) to test TMFs efficacy. This will happen concurrently, since flow treatment and sampling design are intertwined.

Monitoring of trout dispersal

Another key objective of this program is to reduce the dispersal of age 0 trout from Glen Canyon into Marble Canyon. It is likely that small trout move downstream and repopulate Marble Canyon during years when the Lees Ferry fishery has large recruitment events (Yard and Korman, 2017). The downstream movement of small trout appears to be governed by high densities and growth conditions in Glen Canyon (Yard and others, 2015). It is critical to quantify downstream dispersal under both TMF and non-TMF years to determine if this objective is being met. The House Rock reach (17.3-19.5 river miles downstream from Lees Ferry) rarely detects age 0 trout in the electrofishing catch because channel morphology and hydrology are not considered suitable for trout reproduction. Similar data from 2016 from the NO research showed no age 0 in upper and middle Marble Canyon in July but significant numbers in September. In contrast, age 0 were abundant in Glen Canyon on both July and September trips. This pattern shows that movement of age 0 from Glen Canyon occurred in 2016 sometime between July and September. This reach is therefore ideal for monitoring the influx of recruits migrating to and repopulating Marble Canyon. This provides a means to test the assumption underlying the LTEMP model that trout recruitment and downstream dispersal correspond with age 0 recruit densities. This can be accomplished relatively easily based on a comparison of length frequencies in Glen Canyon and Marble Canyon on July and October trips conducted on the JCM mainstem trips (Project G). This design is very similar to what was done under the NO project. Growth between April-July trips and July-October trips will be used to quantify conditions during the high growth period which are potentially affected by spring HFEs, TMFs, and inter-annual trends in nutrient concentrations in flow from GCD. Growth over these periods in years when such flows are conducted can be compared to those when they are not. The logistical cost is not included in this proposal but is identified here due to the linkage between this project and the JCM project.

Contingency plan for TMFs

The TELS study component remains as a contingency plan should management agencies implement a TMF during the FY2018-20 period. The primary objective of this component is to directly measure differences in mortality rates of age 0 rainbow trout and brown trout caused by TMFs across different habitat types (low- and high-angle shoreline). To minimize project costs, the TELS component will be funded from the Experimental Funds during years if TMFs are implemented. These data are to be used to inform the ExTMF model. Age 0 fish will be sampled during the seven days before and seven days after each TMF using a combination of backpack and boat-mounted electro-shocking equipment. In each reach, spatially referenced sites will be continuously distributed on the left and right bank and cover a total of 1-km of shoreline such that low-angle shoreline is present on one side and high-angle shoreline is present on the other. Small fish (40-74 mm) will be marked using a combination of VIE tags, fin clips, and dye marks, while large fish (≥ 75 mm) will be marked with PIT tags. Age 0 trout abundance will be estimated using spatially-stratified mark-recapture data in a closed population modeling framework. Abundance estimates will be made between and within reaches representing low-angle and high-angle shoreline.

Since TMFs are likely to result in significant age 0 mortality, potential compensatory survival responses following TMFs could lead to little change in recruitment for that year as measured in the fall. Thus the TRGD PIT-tagging based estimate of recruitment is also needed to determine if higher mortality from the TMFs as measured by the TELS component of the study ultimately translates into lower recruitment. For the small trout ≤ 75 mm, these closed population estimates will be used in combination with an open population model to estimate abundance, recruitment, growth, and survival in each reach. Sampling multiple reaches provides a means to assess the variability in trout response; however, additional replicates of flow treatments across years will be required in order make inferences on the effect of this prescriptive measure.

In sum, this overall study project will contribute to a better understanding of factors affecting rainbow trout and brown trout population dynamics and seasonal growth in Glen Canyon, which in turn may be controlled by flow and LTEMP ROD experiments. This study will measure seasonal variation in the growth of trout in Glen Canyon. Drift rate measurements taken on each trip will be used to better define the relationship between trout growth and drift rates (Project F). We will also relate estimates of trout growth to other covariates like gross primary production and nutrient levels (Project E). This study continues to monitor the influx of trout recruits (rainbow trout and brown trout) migrating to and repopulating Marble Canyon (Project G). The TELS component is a contingency plan, should TMFs be implemented, that is designed to assess the stranding effects on age 0 trout mortality. To minimize project costs, the TELS component will be funded from the Experimental Funds. Lastly, the purpose of the ExTMF study component is to develop a predicative model for selecting alternative sets of TMFs to experimentally test the efficacy of age 0 trout stranding. Overall, these integrated sampling and modeling efforts will provide insights on the mechanism by which flow and non-flow factors (e.g. nutrients, primary production) control the trout population.

Project Element H.2. Rainbow and brown trout recruitment and outmigration model

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The overall goal of this element is to continue to improve upon the fisheries models used to evaluate LTEMP alternatives. This model will fulfill a number of important needs including: 1) providing predictions for recruitment in upcoming years as one trigger for trout management flows, 2) synthesizing and updating understanding of the drivers of fisheries population dynamics, including the relative role of experimental flow treatments, as new data are collected, and 3) providing a framework to incorporate components not included in past modeling (e.g., brown trout, nutrients). In order to meet these various needs, we will: 1) modify the previous model so that it can incorporate multiple types of data, 2) develop a brown trout portion of the model with a similar structure to the rainbow trout portion, and 3) consider multiple competing hypotheses about drivers of both rainbow and brown trout in the forms of different model versions and update support for these different hypotheses based on data collected during each year.

The ability to predict the strength of rainbow trout recruitment and outmigration relative to management alternatives outlined in the LTEMP BiOp (USDOI, 2016a) is of central importance to effective management of multiple resources in the CRe. Flow alternatives outlined in LTEMP include TMFs, HFEs and macroinvertebrate production flows, which may directly or indirectly effect the rainbow trout population in Lees Ferry. TMFs are designed to increase mortality of YOY rainbow trout, by stranding a portion of the population in low-angle shorelines with the aim of decreasing recruitment and ultimately outmigration. Outmigration of rainbow trout from Lees Ferry to downstream areas, particularly near the LCR confluence, is seen as detrimental to native fish conservation goals. Although the overall emigration rate is small, large recruitment events can lead to increased outmigration (Korman and others, 2015). HFEs and other flows, such as equalization flows, may indirectly effect the rainbow trout population, via increased YOY habitat or increased food availability. For example, large numbers of recruits were observed following years with spring-timed HFEs or higher than average equalization flows, likely driven by increased juvenile survival and growth, resulting from increased food availability or habitat (Cross and others, 2013; Kennedy and others, 2014; Avery and others, 2015). Macroinvertebrate production flows are designed to improve insect production, which will likely benefit rainbow trout, but may also benefit humpback chub downstream. Assessing the potential tradeoffs associated with macroinvertebrate production flows requires an understanding of effects on both rainbow trout outmigration and humpback chub dynamics downriver. Releases from GCD under the LTEMP flow alternative may influence rainbow trout recruitment and outmigration and monitoring these responses has a large bearing on the effective management of resources in the CRe.

Other non-flow factors, including nutrients and trout density likely also play an important role in determining recruitment and outmigration, but have been subject to much less investigation (but see Project E). Variation in the concentration of nutrients (especially phosphorous) correlates to variation in invertebrate drift and initial analysis of recruitment over the last fifteen years suggests that concentrations of SRP is the single best predictor of rainbow trout recruitment (Yackulic, *unpublished data*). Across many western tailwater fisheries, the density of conspecifics can influence growth and other aspects of population dynamics (Dibble and others, 2015). For instance, intraspecific competition for invertebrate drift may increase under higher trout densities, decreasing growth rates and playing a role in both recruitment and outmigration dynamics.

The annually updatable recruitment and outmigration model will be used to test hypotheses related to different factors including both flow and non-flow factors. The model is designed to integrate data from different research and monitoring schemes including long-term catch per effort, RTELSS, NO, and the proposed monitoring scheme (Project Elements H.1, H.4). In addition, we will extend the model to incorporate our emerging understanding of drivers of brown trout population dynamics. We envision a similar structure for the brown trout portion of the model with interactions between the two species and multiple different versions of the model to incorporate different hypotheses about drivers for both species.

Project Element H.3. Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon

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David Rogowski, Fish Biologist, Arizona Game and Fish Department

The objective of this research is to fill critical information needs pertaining to trout early life-history strategies and growth responses to experimental flow manipulation to inform management of brown trout and rainbow trout in Glen Canyon. In this project YOY otoliths will be used to examine: 1) rainbow trout early life history vital rates to inform recruitment models; 2) brown trout hatch and emergence dates to inform the timing of experimental flows; and 3) the immediate physiological response of brown trout to HFEs and TMFs, including variations in responses due to flow timing and duration. Results will identify when brown trout are most vulnerable to flow manipulation to develop tools to manage this aquatic invader.

The LTEMP and its associated ROD identified flow manipulation as a potential tool to regulate rainbow trout recruitment and enhance endangered humpback chub populations in Grand Canyon. In the past, the RTELSS project collected data on vital rates and monitored the response of rainbow trout to nonnative fish suppression flows (2003–2005), equalization flows (2011), and spring and multiple fall-timed HFEs (2008, 2011-2014, 2016; Korman and others, 2011;

Avery and others, 2015). Vital rate data has provided a more mechanistic understanding of downstream emigration events and population-level changes in adult rainbow trout in Grand Canyon (Korman and others, 2011; Korman and others, 2012; Melis and others, 2012), so we propose to continue collecting a limited amount of rainbow trout early life history information in conjunction with quarterly mark-recapture trips in FY2018-19 (Project Element H.1).

Although the RTELSS program has provided useful information pertaining to the response of YOY rainbow trout to flow manipulation, this information is not necessarily analogous to brown trout since the two species have different life history strategies (fall spawning brown trout, spring spawning rainbow trout). Since we lack basic life history data for YOY brown trout in Glen Canyon, we propose to determine brown trout hatch and emergence dates via back-calculation using brown trout otoliths (Korman and others, 2011). YOY brown trout will be collected quarterly in collaboration with the TRGD project and during pre- and post-TMF sampling from FY2018-19, with additional specimens collected in summer and fall during AGFD trout monitoring trips (Project Elements H.1, H.4). Results will be published in FY2020 and will inform the timing of future TMFs and HFEs to target periods when brown trout are emerging from gravel redds and may be vulnerable to stranding on low-angle shorelines.

In addition to the timing of experimental flows, the magnitude and duration of TMFs and HFEs are likely to elicit an immediate growth response that may influence the species' survival, and by extension, cohort strength the following year. Brown trout will be sampled post-TMF or post-HFE in collaboration with the TRGD/TELS projects (Project Element H.1) and on AGFD summer or fall monitoring trips (Project Element H.4) during years in which experimental flows occur. Since otoliths record a daily history of growth between each increment, we will prepare post-flood otoliths for microstructural analysis and calculate daily growth rate in the week leading up to, during, and after each flood (Secor and others, 1991; Gilliers and others, 2004; Amara and others, 2009). In addition, otoliths will be checked for a "check" (a dark line indicating daily growth rings are placed very close together) to determine whether growth was interrupted in response to environmental conditions. Growth rate measurements will be compared to those from fish captured during non-TMF and non-HFE years to account for normal seasonal fluctuations that occur regardless of the occurrence of experimental flows. Biological variables including fish density will be incorporated into models to account for density-dependence effects on growth. Collectively, this data can be used to assess the effectiveness of experimental flows as a tool to manage brown trout populations.

All rainbow trout and brown trout otolith work proposed in this project element will minimize loss of life to the extent practicable by utilizing incidental mortalities and fish collected and euthanized per NPS conditions on permits for GCMRC and its cooperators. In addition, we will coordinate sampling efforts with research and monitoring activities proposed in Project Elements H.1 and H.4 to take advantage of incidental mortalities thereby reducing loss of life per Tribal concerns. In addition, to the extent possible, brown trout specimens will be utilized for the joint purpose of determining hatch and emergence dates (objective #2) and quantifying growth in response to experimental floods (objective #3) to minimize loss of life and to reduce costs associated with this project element.

Project Element H.4. Rainbow trout monitoring in Glen Canyon

David Rogowski, Fish Biologist, Arizona Game and Fish Department

The fish community downriver of GCD has been sampled by AGFD using electrofishing methods since the early 1980s (Maddux and others, 1987), which were standardized in 1991. This program was originally designed to detect population level changes in the rainbow trout fishery over a five-year time scale and has provided long-term trend data used to manage the rainbow trout fishery (McKinney and others, 2001; Makinster and others, 2011). This program underwent refinements following PEPs in 2000, 2009, and 2016 (Anders and others, 2001; Bradford and others, 2009). The 2016 PEP recommended continuing to collect long-term trend data in Lees Ferry (this project) while also incorporating mark-recapture methods into the sampling design to estimate vital rates (Project Element H.1).

The objective of this project is track the status and trends of rainbow trout in the Lees Ferry section of Glen Canyon National Recreation Area and continue to gather long-term trend data on relative abundance, size composition, distribution, recruitment, and angler satisfaction and catch quality. We propose to conduct two sampling trips per year (summer and autumn) to assess the status and trends of the fish population using CPUE metrics. During these trips, 40 sites will be sampled using a random stratified design based on subreaches (upper, middle, lower). In lieu of a spring trip (as has been done in the past), we will add a night of sampling to the autumn trip to focus on the detection, status, and population trends of rare nonnative species including brown trout in Glen Canyon (Project Element I.2). The summer trip will include both rainbow trout and nonnative monitoring components as we have conducted the past few years. The addition of a night of targeted sampling for rare-nonnatives in conjunction with our normal summer and autumn monitoring effort will provide the opportunity to rapidly respond to new aquatic invaders (e.g., green sunfish; *Lepomis cyanellus*).

In addition to the proposed monitoring using standardized electrofishing methods, we will conduct angler creel surveys to estimate angler effort, catch, and harvest on an annual basis. As was done in the FY2015-17 work plan, we propose that creel surveys be funded by the GCDAMP in FY2018-19 and by AGFD in FY2020. Creel surveys will be scheduled on a monthly and weekend/weekday basis to allocate survey effort relative to angling effort during the year. These interviews will be conducted near the boat ramp for anglers fishing in the upriver section (between GCD and the Lees Ferry boat ramp) and in the walk-in section (from the Lees Ferry boat ramp downstream to the Paria River). The angler surveys provide data on angler catch rate, including angler estimates of fish ≥ 14” and fish ≥ 20” in length; however, angler estimates do not provide accurate length information associated with the catch, thus AGFD cannot accurately assess whether goals related to angler catch quality are being met. Therefore, we propose a new citizen science project to assess whether goals related to angler catch quality are being met by utilizing fishing guides to collect length data on fish caught by clients. Participating guides will measure fish caught by clients on randomly selected (to the extent practicable due to guiding schedules) weekend days and weekdays, and will be paid ~$10/day for participating. Guides will measure all fish caught in a day to ensure a representative sample. AGFD is conducting a small pilot project this year (2017), with 2–3 guides collecting length information on a total of 20–30 days. The pilot study will allow us to refine our methods and data collection as needed to obtain accurate length information and minimize guide time commitment. For FY2018–20 AGFD plans to expand the citizen science project to more guides and more sample days. Exact numbers of guides and days will depend on guide interest and desired sample size (informed by 2017 data).

5.2. Deliverables

Project H will evaluate how experimental flows (macroinvertebrate production flows, HFEs, and other LTEMP flow experiments) influence recruitment, growth, survival, and dispersal of rainbow and brown trout in Glen Canyon. Each of the four project elements as described will result in one or more peer-reviewed journal articles and presentations at scientific meetings. These project elements use a number of different fishing methods and analyses that further advance our overall understanding of aquatic ecology, and the outcome of several of these project elements will be the publication of papers in top-tier scientific journals. We will also provide annual summaries of state variables and vital rates (e.g., abundance, CPUE, survival, recruitment, and growth rates) at the Annual Reporting Meeting each January. Also, we can provide more frequent summaries of these key monitoring metrics to the TWG and stakeholder groups, if there is additional interest in further evaluating the response of trout to any combination of LTEMP flow experiments.

5.3. Personnel and Collaborations

The overall project lead for Project H is Dr. Michael Yard, a Fish Biologist at GCMRC who specializes in rainbow trout population dynamics and statistical modeling. Dr. Charles Yackulic is a Research Statistician specializing in population dynamics with an emphasis in modeling linkages and vital rates between trout populations. Dr. Josh Korman is a Fish Biologist with Ecometric Research Inc. specializing in analytical models and database development, population dynamics, and modeling capabilities. Dr. Kimberly Dibble is Fish Biologist at GCMRC with expertise in fish physiology, otolith microstructural analysis, and metadata analysis. Dr. David Rogowski is a Fish Biologist with the Arizona Game and Fish Department and is responsible for some of the long-term fish monitoring programs in Glen and Grand Canyons and is experienced in statistical models and database management. Clay Nelson is a Fish Biologist at GCMRC who has extensive field experience working with native and introduced fishes in Glen and Grand Canyons. Dr. Ken Sheehan is a Fish Biologist at GCMRC who specializes in habitat modeling and linkages to aquatic organisms and environmental spatial analysis. Michael Dodrill is a Fish Biologist with expertise in fish habitat and trout bioenergetics modeling.

6. References

Amara, R., Selleslagh, J., Billon, G., and Minier, C., 2009, Growth and condition of 0-group European flounder, *Platichthys flesus* as indicator of estuarine habitat quality: Hydrobiologia, v. 627, p. 87-98, http://dx.doi.org/10.1007/s10750-009-9717-9.

Anders, P., Bradford, M.c., Higgins, P., Nislow, K.H., Rabeni, C.F., and Tate, C., 2001, Grand Canyon Monitoring and Research Center protocols evaluation program (PEP)—Final report of the Aquatic Protocol Evaluation Program panel: Flagstaff, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 43 p., http://www.gcmrc.gov/library/reports/PEP/Anders2001.pdf.

Avery, L.A., Korman, J., and Persons, W.R., 2015, Effects of increased discharge on spawning and age-0 recruitment of rainbow trout in the Colorado River at Lees Ferry, Arizona: North American Journal of Fisheries Management, v. 34, no. 4, p. 671-680, http://dx.doi.org/10.1080/02755947.2015.1040560.

Bligh, E.G., and Dyer, W.J., 1959, A rapid method of total lipid extraction and purification: Canadian Journal of Biochemistry and Physiology, v. 37, no. 8, p. 911-917, https://doi.org/10.1139/o59-099.

Bradford, M., Bevelhimer, M., Hansen, M., Mueller, G., Osmundson, D., Rice, J.A., and Winkelman, D., 2009, Report of the 2009 Protocol Evaluation Panel (PEP) for fish monitoring programs of the Grand Canyon Monitoring and Research Center: Flagstaff, Ariz., submitted to U.S. Geological Survey, Grand Canyon Monitoring Research Center, 41 p., https://www.usbr.gov/uc/rm/amp/twg/mtgs/12jun20/Attach_06a.pdf.

Budy, P., Thiede, G.P., McHugh, P., Hansen, E.S., and Wood, J., 2008, Exploring the relative influence of biotic interactions and environmental conditions on the abundance and distribution of exotic brown trout *(Salmo trutta)* in a high mountain stream: Ecology of Freshwater Fish, v. 17, no. 4, p. 554-566, http://dx.doi.org/10.1111/j.1600-0633.2008.00306.x.

Cattanéo, F., Lamouroux, N., Breil, P., and Capra, H., 2002, The influence of hydrological and biotic processes on brown trout *(Salmo trutta)* population dynamics: Canadian Journal of Fisheries and Aquatic Sciences, v. 59, no. 1, p. 12-22, http://dx.doi.org/10.1139/F01-186.

Cleary, J.S., Bradford, M.J., and Janz, D.M., 2012, Seasonal and spatial variation in lipid and triacylglycerol levels in juvenile chinook salmon *(Oncorhynchus tshawytscha)* from the Bridge River, British Columbia: Limnologica-Ecology and Management of Inland Waters, v. 42, no. 2, p. 144-150, https://doi.org/10.1016/j.limno.2011.10.003.

Coggins, L.G., Yard, M.D., and Pine, W.E., 2011, Nonnative fish control in the Colorado River in Grand Canyon, Arizona—An effective program or serendipitous timing?: Transactions of the American Fisheries Society, v. 140, no. 2, p. 456-470, http://dx.doi.org/10.1080/00028487.2011.572009.

Cross, W.F., Baxter, C.V., Rosi-Marshall, E.J., Hall, R.O., Jr., Kennedy, T.A., Donner, K.C., Wellard Kelly, H.A., Seegert, S.E.Z., Behn, K., and Yard, M.D., 2013, Food-web dynamics

in a large river discontinuum: Ecological Monographs, v. 83, no. 3, p. 311-337, http://dx.doi.org/10.1890/12-1727.1.
Dibble, K.L., Yackulic, C.B., Kennedy, T.A., and Budy, P., 2015, Flow management and fish density regulate salmonid recruitment and adult size in tailwaters across western North America: Ecological Applications, v. 25, no. 8, p. 2168-2179, http://dx.doi.org/10.1890/14-2211.1.
Gilliers, C., Amara, R., and Bergeron, J.-P., 2004, Comparison of growth and condition indices of juvenile flatfish in differentcoastal nursery grounds: Environmental Biology of Fishes, v. 71, no. 2, p. 189-198, http://dx.doi.org/10.1007/s10641-004-0090-2.
Hearn, W.E., 2011, Interspecific competition and habitat segregation among stream-dwelling trout and salmon—A review: Fisheries, v. 12, no. 5, p. 24-31, http://dx.doi.org/10.1577/1548-8446(1987)012<0024:ICAHSA>2.0.CO;2.
Jonsson, B., and Jonsson, N., 2009, A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow: Journal of Fish Biology, v. 75, no. 10, p. 2381–2447, http://dx.doi.org/10.1111/j.1095-8649.2009.02380.x.
Kaspersson, R., Sundström, F., Bohlin, T., and Johnsson, J.I., 2013, Modes of competition—Adding and removing brown trout in the wild to understand the mechanisms of density-dependence: PloS One, v. 8, no. 5, e62517, p. 1-9, https://doi.org/10.1371/journal.pone.0062517.
Kennedy, T.A., Yackulic, C.B., Cross, W.F., Grams, P.E., Yard, M.D., and Copp, A.J., 2014, The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river: Freshwater Biology, v. 59, no. 3, p. 557-572, http://dx.doi.org/10.1111/fwb.12285.
Korman, J., Kaplinski, M., and Melis, T.S., 2011, Effects of fluctuating flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society, v. 140, no. 2, p. 487-505, http://dx.doi.org/10.1080/00028487.2011.572015.
Korman, J., Martell, S.J.D., Walters, C.J., Makinster, A.S., Coggins, L.G., Yard, M.D., and Persons, W.R., 2012, Estimating recruitment dynamics and movement of rainbow trout *(Oncorhynchus mykiss)* in the Colorado River in Grand Canyon using an integrated assessment model: Canadian Journal of Fisheries and Aquatic Sciences, v. 69, no. 11, p. 1827-1849, http://dx.doi.org/10.1139/F2012-097.
Korman, J., Yard, M., Walters, C.J., and Coggins, L.G., 2009, Effects of fish size, habitat, flow, and density on capture probabilities of age-0 rainbow trout estimated from electrofishing at discrete sites in a large river: Transactions of the American Fisheries Society, v. 138, no. 1, p. 58-75, http://dx.doi.org/10.1577/T08-025.1.
Korman, J., and Yard, M.D., 2017a, Trends in rainbow trout recruitment, abundance, survival, and growth during a boom-and-bust cycle in a tailwater fishery: Transactions of the American Fisheries Society, early view, available at http://dx.doi.org/10.1080/00028487.2017.1317663.
Korman, J., and Yard, M.D., 2017b, Effects of environmental covariates and density on the catchability of fish populations and interpretation of catch per unit effort trends: Fisheries Research, v. 189, p. 18-34, https://doi.org/10.1016/j.fishres.2017.01.005.
Korman, J., Yard, M.D., and Yackulic, C.B., 2016, Factors controlling the abundance of rainbow trout in the Colorado River in Grand Canyon in a reach utilized by endangered humpback

chub: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 105-124, http://dx.doi.org/10.1139/cjfas-2015-0101.

Maddux, H.R., Kubly, D.M., deVos, J.C., Jr., Persons, W.R., Staedicke, R., and Wright, R.L., 1987, Effects of varied flow regimes on aquatic resources of Glen and Grand Canyons—final report: Phoenix, Arizona Game and Fish Department, unpublished report submitted to Bureau of Reclamation, Glen Canyon Environmental Studies, contract no. 4-AG-40-01810, 291 p., http://www.gcmrc.gov/library/reports/Biological/Fish_Studies/Maddux1987.pdf.

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/.

McKinney, T., Speas, D.W., Rogers, R.S., and Persons, W.R., 2001, Rainbow trout in a regulated river below Glen Canyon Dam, Arizona, following increased minimum flows and reduced discharge variability: North American Journal of Fisheries Management, v. 21, no. 1, p. 216-222, http://dx.doi.org/10.1577/1548-8675(2001)021<0216:RTIARR>2.0.CO;2.

Melis, T.S., Korman, J., and Kennedy, T.A., 2012, Abiotic and biotic responses of the Colorado River to controlled floods at Glen Canyon Dam, Arizona, USA: River Research and Applications, v. 28, no. 6, p. 764-776, http://dx.doi.org/10.1002/rra.1503.

Mueller, G.A., 2005, Predatory fish removal and native fish recovery in the Colorado River mainstem—What have we learned?: Fisheries, v. 30, no. 9, p. 10-19, http://dx.doi.org/10.1577/1548-8446(2005)30[10:PFRANF]2.0.CO;2.

Rogers, S. 2015. Fisheries management plan Colorado River-Lees Ferry 2015-2025. Region II Fish Program, Phoenix, AZ, 15 p., https://www.usbr.gov/uc/rm/amp/twg/mtgs/15oct20/.

Parrish, C., 1999, Determination of total lipid, lipid classes, and fatty acids in aquatic samples, *in* Arts, M.T., and Wainman, B.C., eds., Lipids in freshwater ecosystems: New York, Springer-Verlag, p. 4-20, https://link.springer.com/chapter/10.1007%2F978-1-4612-0547-0_2.

Persons, W.R., Ward, D.L., and Avery, L.A., 2012, Standard methods for Grand Canyon fisheries research 2012: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 43 p., http://www.fwspubs.org/doi/suppl/10.3996/122011-JFWM-070/suppl_file/10.3996_122011-jfwm-070.s2.pdf?code=ufws-site.

Secor, D.H., Dean, J.M., and Laban, E.H., 1991, Otolith removal and preparation for microstructural examination—A users manual: Cambridge, Md., Electric Power Research Institute and Belle W. Baruch Institute for Marine Biology and Coastal Research, no. 1991-01, available at https://www.cbl.umces.edu/~secor/otolith-manual.html.

Smokorowski, K.E., and Randall, R.G., 2017, Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs: FACETS, v. 2, p. 212-232, http://dx.doi.org/10.1139/facets-2016-0058.

Strange, E., and Foin, T.C., 1999, Interaction of physical and biological processes in the assembly of stream fish communities, *in* Weiher, E., and Keddy, P.A., eds., Ecological assembly rules—Perspectives, advances, retreats: Cambridge, Cambridge University Press, p. 311-337 https://doi.org/10.1017/CBO9780511542237.012.

U.S. Department of the Interior, 2016a, U.S. Fish and Wildlife Service Biological Opinion (BiOp)—Appendix E, *in* Record of Decision (ROD) for the Glen Canyon Dam Long-term

Experimental Plan final Environmental Impact Statement (LTEMP FEIS): Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, p. E-1—E-94, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Department of Interior, 2016b, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

U.S. Department of Interior, 2016c, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Wenger, S.J., Isaak, D.J., Luce, C.H., Neville, H.M., Fausch, K.D., Dunham, J.B., Dauwalter, D.C., Young, M.K., Elsner, M.M., Rieman, B.E., Hamlet, A.F., and Williams, J.E., 2011, Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change: Proceedings of the National Academy of Sciences, v. 108, no. 34, p. 14175-14180, http://dx.doi.org/10.1073/pnas.1103097108.

Yackulic, C.B., Korman, J., Yard, M.D., and Dzul, M.C., *in review*, Inferring species interactions through joint mark-recapture analysis: Ecology.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, J., 2011, Trout piscivory in the Colorado River, Grand Canyon—Effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society, v. 140, no. 2, p. 471-486, http://dx.doi.org/10.1080/00028487.2011.572011.

Yard, M.D., Korman, J., Walters, C.J., and Kennedy, T.A., 2016, Seasonal and spatial patterns of growth of rainbow trout in the Colorado River in Grand Canyon, Arizona: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 125-139, http://dx.doi.org/10.1139/cjfas-2015-0102.

Yard, M.D., and Korman, J., 2017, A synthesis—What we have learned about rainbow trout movement, growth, survival over the study period that has implications to management—Natal origin project: Glen Canyon Dam Adaptive Management Program annual reporting meeting presentation, Phoenix, AZ, January 25, 2017, https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR16_Yard.pdf.

7. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
H	*Salmonid Research and Monitoring*								
H.1	Experimental flow assessment of trout recruitment	$188,594		$25,160	$101,492	$60,000		$50,843	$426,089
H.2	Rainbow and brown trout recruitment and outmigration model	$73,693						$11,464	$85,157
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$41,266		$300		$18,285		$7,015	$66,866
H.4	Rainbow trout monitoring in Glen Canyon				$15,952	$84,000		$5,002	$104,954
	Total H	**$303,552**	**$0**	**$25,460**	**$117,444**	**$162,285**	**$0**	**$74,324**	**$683,065**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
H	*Salmonid Research and Monitoring*								
H.1	Experimental flow assessment of trout recruitment	$195,119	$7,420	$22,410	$111,092	$60,000		$89,171	$485,212
H.2	Rainbow and brown trout recruitment and outmigration model	$41,715						$10,846	$52,561
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$26,558		$600		$43,616		$8,370	$79,144
H.4	Rainbow trout monitoring in Glen Canyon				$17,652	$84,000		$7,110	$108,762
	Total H	**$263,392**	**$7,420**	**$23,010**	**$128,744**	**$187,616**	**$0**	**$115,496**	**$725,679**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
H	*Salmonid Research and Monitoring*								
H.1	Experimental flow assessment of trout recruitment	$187,143	$7,236	$25,160	$113,864	$60,000		$88,485	$481,888
H.2	Rainbow and brown trout recruitment and outmigration model	$5,642						$1,467	$7,109
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$79,255						$20,606	$99,861
H.4	Rainbow trout monitoring in Glen Canyon				$18,462	$84,000		$7,320	$109,782
	Total H	**$272,040**	**$7,236**	**$25,160**	**$132,326**	**$144,000**	**$0**	**$117,878**	**$698,640**

8. Experimental Project Budget (see Appendix 2e)

The proposed budget to support the research and monitoring of TMF experiment in FY2018-20. The annual experimental fund would cover costs associated with additional logistics, field personnel, and data processing required for the TELS study component. Reporting would be covered by existing projects. Some work will be conducted as part of other planned research and monitoring trips. The costs below are hypothetical and based on projected USGS FY2019 salaries and overhead.

9. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element H.(i). Rainbow trout recruitment and outmigration model (FY2020 funding eliminated; $29,700).

Project I. Warm-Water Native and Non-Native Fish Research and Monitoring

1. Investigators

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2. Project Summary

Two specific resource goals outlined in the LTEMP EIS and associated BiOp for operation of GCD are maintenance of self-sustaining native fish populations within the Colorado River and minimizing the presence and expansion of aquatic invasive species (USDI 2016). Declines in native fish populations throughout the southwest are commonly linked to adverse interactions with invasive warm-water fish (Marsh and Pacey, 2005, Clarkson and others 2005). In the Colorado River, and especially the upper Colorado River, warm-water predatory fish are implicated in lack of recruitment and population declines in native fish (Martinez and others 2014). For this reason, regulation and control of invasive fish is an important action identified in all recovery goals for Colorado River endangered fish including humpback chub (USFWS 2002, under revision). This project aims to provide scientific information that facilitates effective warm-water fish management in the following ways:

1) By conducting system-wide fish monitoring to track trends in native fish and by refining existing monitoring efforts and employing new monitoring tools to improve early detection capability of invasive warm-water fish.

2) By assessing and quantifying the relative risks posed by warm-water nonnative fish to humpback chub and other native fish utilizing a combination of field and laboratory research.

Long-term monitoring allows the ability to detect trends and test hypotheses in regard to temporal variation in fish populations, but its strength also lies in the ability to interpret and detect unexpected trends or surprises (Lindenmayer and others, 2010, Dodds and others, 2012, Melis and others, 2015). When designed properly, a long-term monitoring program is a powerful tool for quantifying the status and trends of key resources, understanding system dynamics in response to stressors, and investigating the efficacy of alternative management actions. Without long-term monitoring, science-based decisions for fisheries management are often not possible (Walters 2001).

Preventing new invasions is the least expensive and most effective way to control invasive species when compared to the cost of control projects after invasions occur (Leung and others, 2002). Therefore, we seek to improve detection of potentially problematic warm-water invasive fish within the CRe in Grand Canyon by continuing existing monitoring efforts and testing new Environmental DNA (eDNA) detection tools. We propose to continue monitoring efforts at Lees Ferry by adding an additional night of sampling on both the summer and fall trips to include 12 sites where warm-water species are likely to aggregate and spawn. This will maximize our ability to detect range expansions of existing warm-water invasive species and those that may pass through the dam.

Currently, AGFD conducts system-wide fish monitoring using electrofishing, angling and hoop netting from Lees Ferry (RM 0) to Pearce Ferry (RM 281). Other fish monitoring efforts focus on humpback chub (project G) and other native fishes small-bodied fish monitoring conducted by the NPS downstream of Bright Angel Creek, funded by the Bureau of Reclamation. These projects also provide important detection data related to invasive warm-water fish. As the elevation of Lake Mead has decreased due to drought, the western segment of the river has reemerged, creating the need to extend sampling efforts for native fish as well as invasive species detection for an additional 15 miles to the Lake Mead interface. In this work plan AGFD will conduct two spring system-wide fish monitoring trips per year and a single fish monitoring trip per year in the fall to monitor fish populations downstream of Diamond Creek.

New tools such as eDNA will be tested to validate the presence or absence of key invasive species, determine the spatial extent of invasions within the mainstem Colorado River and estimate the relative biomass of aquatic invaders. Environmental DNA is DNA that is collected from the environment in which an organism lives, rather than directly from animals themselves. In aquatic environments, animals including fish, shed cellular material into the water via reproduction, saliva, urine, feces, etc. This DNA may persist in the environment for several weeks, and can be collected in a water sample which can then be analyzed to determine if the target species of interest are present (Carim and others, 2016).

Ficetola and others (2008) first demonstrated that detection of vertebrates using eDNA in water samples was possible and interest in using this tool to improve detection sensitivity and cost efficiency over aquatic field surveys has grown rapidly and been shown to be effective in many aquatic systems (Goldberg and others 2011). Environmental DNA can have higher sensitivity and lower cost than traditional sampling methods especially when attempting to detect very rare organisms. Water samples for eDNA analysis are relatively easy to collect in conjunction with exiting monitoring trips and data can be paired with standard electrofishing and hoop netting data to compare the sensitivity of each approach. Investigating the utility of new eDNA detection tools is a critical first step in preventing the establishment and spread of warm-water invasive fish in CRe because it may allow early detection of new invasive species so that management actions can be targeted to prevent their spread.

Management and removal of invasive aquatic species can be difficult once a species becomes established because of the large scale of the problem and the few effective tools that are available (Dawson and Kolar 2013). This creates the need to understand which species pose the greatest threats. Assessing the risks posed by existing or new warm-water invasive fish provides managers with the scientific information needed to make decisions about what management activities are warranted. Hilwig and Andersen (2011), compiled a literature review of the potential risks posed by individual species, but those risks need to be validated and quantified based on existing environmental conditions, species abundances, and expected future conditions in the LCR and CRe. Although extensive research to evaluate rainbow trout and brown trout predation on juvenile humpback chub under various environmental conditions was conducted in the previous work plan, other warm water invasive species in the LCR may also be detrimental to humpback chub and other native fish. To that end, risks posed by other warm-water invasive fish such as channel catfish (*Ictalurus punctatus*) and bullhead catfish (*Amerius melas*) will be quantified using diet analysis and modeling. Laboratory studies will be conducted to quantify predation risk from common carp (*Cyprinus carpio*) and small bodied fish such as fathead minnow and plains killifish (*Fundulus zebrinus*) (on humpback chub eggs and larvae). These studies will determine if warm-water invasive fish present more or less of a predation threat to juvenile chub than predation by trout. This information gives context from which to evaluate potential management actions such as trout removal and will ensure that any future aquatic invasive species removal efforts are focused only on those species that pose the highest threat to humpback chub populations.

In addition to evaluating the risks posed by invasive fish species we will also evaluate the risks posed by infestation of Asian fish tapeworm (*Bothriocephalus acheilognathi*) in humpback chub. Asian fish tapeworm is an invasive species that infests warm-water cyprinid fish. Asian fish tapeworm monitoring has occurred annually within the LCR and additional monitoring will be conducted in this work plan on Asian fish tapeworm in humpback chub inhabiting the mainstem Colorado River as identified in the 2016 BiOp. Asian fish tapeworm has been identified as one of six potential threats to the continued existence of endangered humpback chub (USFWS 2002). It is potentially fatal to new host species (Hoffman and Schubert 1984). Asian fish tapeworm was first documented in the LCR in Grand Canyon in 1990 (Minckley 1996) and was hypothesized to be a cause of long-term declines in condition of adult humpback chub from the LCR (Meretsky and others 2000). Monitoring Asian fish tapeworm infestation in humpback chub in the mainstem Colorado River will provide a baseline context and relative risk assessment with which to evaluate the potential impacts of this invasive parasite on humpback chub populations.

3. Hypotheses and Science Questions

Element I.1.

What is the species composition, relative abundance, longitudinal distribution and population trend of the fish community inhabiting the CRe?

What is the incidence of infestation of Asian fish tapeworm in humpback chub in the mainstem Colorado River and what risks does this parasite pose?

Element I.2.

What warm-water nonnative fishes are present in the CRe and how can we improve our ability to detect new invasions of warm-water nonnative fish before they become established?

Element I.3.

What are the impacts of warm-water nonnative fish on juvenile humpback chub within the LCR and are those impacts more or less of a threat than predation by trout?

4. Background

Prior to construction of GCD water temperature in the Colorado River in Grand Canyon historically fluctuated from near freezing in the winter to almost 30°C in the summer (Vernieu and others 2005). During this period, the Colorado River was dominated by native fish and introduced warm-water fish such as channel catfish (Hayden 1992, Minckley and Marsh 2009). These warm-water fish can handle cold winter water temperatures but need warmer water to grow and complete their life cycle. With the completion of GCD in 1963 and subsequent filling of Lake Powell, river temperatures dropped to 7-10°C by 1973 with little annual variation. This shift in the thermal regime dramatically altered the fish assemblage of the Colorado River in Grand Canyon, changing it from an assemblage dominated by warm-water species to one dominated by cold-adapted rainbow trout for many years. Constant cold water has kept warm-water introduced fish from becoming established throughout Glen, Marble and most of Grand Canyon. Cold water releases from Lake Powell persisted from 1983, when the reservoir filled completely, until 2005 when drought conditions caused water elevations in Lake Powell to drop and warmer surface waters became entrained in the penstocks and released downstream (8 – 16°C), once again creating a varied thermal regime in the Colorado River in Glen, Marble and Grand Canyons for several years. This short period of warmer water within a system dominated by cold water may be one reason for the unique pattern of native fish increases in recent years in the CRe, compared to dramatic declines that have occurred in most other portions of the Colorado River Basin during the same time period.

In cooperation with the AGFD, fish community monitoring occurs annually in the spring from GCD to the Lake Mead inflow (482 kilometers) using a variety of methods: boat-mounted, DC electrofishing conducted at night, angling below the LCR, and hoop nets. Methods were standardized in 2000 and employ a stratified random sampling design to provide a catch-per-unit-effort index of abundance for the fish species that are present (Speas and others 2003). This long-term system wide monitoring program provides the baseline context under which population changes can be compared and assessed. We propose to continue this long-term system-wide monitoring because it provides important trend information on multiple species of native and nonnative fish throughout the CRe. This monitoring program also provides detection capability for new warm-water invasive fish which may be entering the CRe from Lake Powell, by passing through GCD, by descending tributaries such as the LCR, or swimming upstream from Lake Mead.

Identifying sources of warm-water invasive fish in the CRe early improves the likelihood that a successful rapid containment/eradication response can be accomplished before negative impacts on endangered populations occur (Martinez and others 2014). Preventing the introduction and spread of warm-water invasive fish is far more environmentally and fiscally desirable than undertaking control or eradication efforts after they become established (Martinez and others 2014, Cucherousset and Olden 2011). Invasive fish have high proliferative potential, and once established, eradication is often essentially impossible and control typically requires long-term and expensive efforts (Martinez and others 2014, Pimentel and others 2000; Simberloff 2003; Mueller 2005; Johnson and others 2009; McIntosh and others 2010). As indicated in the 2016 BiOp for the LTEMP EIS, the Bureau of Reclamation will conduct planning and compliance for implementation of rapid response control efforts for newly establishing or existing deleterious invasive species within and contiguous to the action area (USDI 2016). Before any management actions can occur monitoring must first detect those invasions and research must be conducted to evaluate risks and inform managers whether or not control efforts are actually warranted. This project provides for the integration of monitoring, research, and invasive species management.

5. Proposed Work

5.1. Project Elements

Project Element I.1. System-wide native fish and invasive aquatic species monitoring

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David Ward, Fish Biologist, U.S. Geological Survey

The primary objective of this project element is to provide long-term data collection on the longitudinal distribution and status of the fish community in the mainstem Colorado River from Lees Ferry (RM 0) to Lake Mead (RM 281). System-wide monitoring is necessary to assess populations of native fish and to monitor the status of nonnative fish to ensure that associated

LTEMP goals are met. Annually, AGFD has been conducting two spring river trips from Lees Ferry to Diamond Creek, and one fall river trip from Diamond Creek to Pearce Ferry and uses standardized electrofishing, hoop netting catch, and angling CPUE indices to track the relative status and trends of most common native and nonnative fish species in the CRe. The current work plan will continue this same monitoring at a slightly reduced level for the spring monitoring trips because of budget constraints (12 nights of sampling per trip instead of 15) and will emphasize monitoring trends in nonnative species. This fish monitoring program was designed to detect population level changes in target fish species (rainbow trout and flannelmouth sucker) over a five-year time scale, although yearly changes in CPUE for these species have been evident. This monitoring effort also tracks catch rates of the other fish present in the system, although the sampling design was not optimized to detect trends in these species. Annual monitoring of native and nonnative fish in the CRe has been ongoing since 2000 (Makinster and others, 2010).

The elevation of Lake Mead has decreased due to drought and the Colorado River has reemerged in areas that were previously inundated. Sampling below RM 225 began in 2007, and below RM 270 in 2015. This section of river is of particular interest because western Grand Canyon holds large numbers of native fish, relative to upstream segments. For this reason, AGFD has increased the spatial extent of its downstream monitoring effort in the reach immediately upstream of Pearce Ferry. Catches of humpback chub and other native species from 2016 hoop netting were highest in the reach from just upstream of Diamond Creek to Pearce Ferry (RM 220 – 281). These results suggest a possible range expansion of humpback chub in western Grand Canyon. Additionally, in 2012 AGFD detected the first razorback sucker in over 20 years in this system, and subsequent detections occurred in 2013 and 2014. The reach downstream from Pearce Ferry to Lake Mead (RM 281 – 296) may also be important habitat for native fish, including the endangered humpback chub and razorback sucker; however, these fish are not being monitored in this area because of Pearce Ferry Rapid at RM 281.4 which poses a navigation hazard.

Annual Asian fish tapeworm monitoring will also be conducted in conjunction with fall fish monitoring efforts. Monitoring of fish parasites such as Asian fish tapeworm is identified as a requirement of the 2016 BiOp for operation of GCD. Thirty to 60 humpback chub of various sizes will be held on the river bank in an 1893-liter collapsible tank and will be treated according to methods described in Ward 2007, where individual fish are held in perforated buckets inside a larger holding tank treated with Praziquantel at 6 mg/l. Each fish will receive two Praziquantel treatments 48 hours apart with the number of tapeworms quantified from each individual fish. Praziquantel has been used since 1985 to remove parasites in many different fish species in hatcheries. Following treatment all fish will be released alive back into the river. These methods are identical to those that have been used in ongoing Asian tapeworm monitoring in the LCR. This monitoring effort will be used to establish an annual baseline infection level by fish size, and used to evaluate the potential impacts of Asian fish tapeworm on humpback chub populations inhabiting the mainstem Colorado River. This information will be used 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 in the mainstem Colorado River.

As part of this work element we also propose to summarize and report on the number of native and nonnative fish that were caught as well as euthanized throughout the CRe annually from all fish monitoring projects. This summary information will quantify the taking of life that occurs within the canyon, in response to tribal concerns, and will also facilitate identification of range expansions or new aquatic invasive species detections that might not be apparent without evaluations across projects conducted by various cooperating agencies.

Project Element I.2. Improve early detection of warm-water invasive fish

Dave Rogowski, Fish Biologist, Arizona Game and Fish Department
Kim Dibble, Fish Biologist, U.S. Geological Survey
Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service

The nonnative species currently present within Grand Canyon are only a fraction of the potential nonnative fish species that could establish themselves in the Colorado River. Many invasive fish that are not yet established in the CRe have caused population declines and even extinctions in the upper Colorado River Basin and in other southwestern river systems (Minckley and Deacon, 1991). For these reasons, methods to improve early detection of warm-water invasive fish species are warranted. This project element proposes to improve detection efficiency by increasing sampling effort at Lees Ferry to detect invasive fish species that are coming downstream through the dam from Lake Powell as well as an evaluation of new eDNA tools to increase detection efficiency in western Grand Canyon for fish moving upstream out of Lake Mead and in from tributaries such as the LCR.

AGFD currently conducts a single targeted nonnative monitoring trip at Lees Ferry in July at 12 locations within the Colorado River near Lees Ferry. We propose to increase this monitoring effort to include an additional night of sampling in the fall in conjunction with rainbow trout monitoring at locations in the river where water temperatures are seasonally higher than in the thalweg or areas known to have had nonnative fish species in the past (e.g. springs, backwaters, and areas just below the dam). This monitoring effort will include electrofishing and minnow trapping conducted at a total of 12 sites.

Traditional field methods including hoop netting and standard electrofishing may not detect rare species at the early stages of invasion, species with low susceptibility to capture, or species residing in deeper areas outside of the range of standard sampling methods. Therefore, we propose to evaluate the use of eDNA technology to increase our ability to detect the presence and relative abundance of aquatic invasive species moving upstream out of Lake Mead into western Grand Canyon and into the mainstem CRe from tributary inputs (Carim and others, 2016;

Goldberg and others, 2011; Klymus and others, 2015). Since mitochondrial DNA from a range of aquatic organisms can persist for up to several weeks in a water body at very low concentrations, we propose to collect this DNA by filtering water samples at sites near tributary junctions and in the western Grand Canyon (Carim and others, 2016). Filtered samples will be preserved in the field and sent to a genome sequencing laboratory to determine if the target species of interest have been present in the CRe. Since the concentration of eDNA in a water body is proportional to the biomass of the aquatic invader, relative abundance can also be estimated (Klymus and others, 2015). In the past, water samples were traditionally tested for a single species of interest (e.g., smallmouth bass) using conventional, isothermal, or quantitative polymerase chain reaction (PCR) methods; however, recent advancements in eDNA technology now allow for the comparison of eDNA sequences in a sample to an online database using a metagenomics approach, which provides data on all of the species in a water sample. Collection of water samples will take place on the annual AGFD system wide fish monitoring trips in conjunction with fish sampling to evaluate the sensitivity of eDNA technology to detecting aquatic invaders. Occupancy models will be developed, if appropriate, using direct capture and eDNA data to examine detection probability and the relative sensitivity of each type of technology. The goal of these monitoring efforts is to improve detection ability and efficiency so that management agencies can deploy resources to rapidly contain or eradicate aquatic invaders before they spread, thereby reducing potential negative impacts to native species.

Project Element I.3. Assess the risks warm-water nonnative fish pose to native fish

David Ward, Fish Biologist, U.S. Geological Survey
Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service

The objective of this project element is to evaluate impacts of warm-water invasive fish on humpback chub in both laboratory and field settings and to determine if these species represent more or less of a predation threat to juvenile chub than predation by trout. Work conducted in the previous work plan focused on the potential negative impacts that rainbow trout and brown trout may have on humpback chub populations through predation and competition (Ward and others 2015, Ward and others 2016) but other warm-water invasive fish are also likely to negatively affect humpback chub populations within the LCR. The potential magnitude of those interactions relative to impacts of trout remains uncertain. Predation on humpback chub by channel catfish and black bullhead catfish has the potential to be high but impacts have not been quantified. Other invasive warmwater species like common carp and fathead minnow (*Pimephales promelas*) may also have detrimental impacts on eggs and early larval stages of humpback chub negatively impacting recruitment. Management actions to control these species may be warranted depending on the magnitude of these interactions. Control of these warm-water invasive fish within the LCR may be more cost effective than trout removal in the mainstem Colorado River if they are having population-level impacts on humpback chub, but these questions have not been evaluated. Relative predation vulnerability of humpback chub to predatory warm-water fish will be assessed in the laboratory in overnight trials using methods similar to those employed for rainbow and brown trout in the previous work plan (Ward and others 2015). Twelve replicate tanks at 20°C will be used to evaluate relative predation vulnerability among species of multiple size classes of juvenile humpback chub to channel catfish, black bullhead catfish, and smallmouth bass during overnight trials using 4 predators and 12 prey fish per tank. Humpback chub eggs and larvae will also be exposed to predation by common carp, fathead minnow and plains killifish in replicated overnight laboratory trials to compare the relative predation risk these predators pose for humpback chub at early life stages. Pilot investigations using standardized protocols indicate predation vulnerability varies highly depending on environmental conditions.

Information collected from this project element gives context within which to evaluate the potential management actions such as trout removal. Hilwig and Andersen (2011) provided a comprehensive literature review of potential risks posed by individual species but these risks also need to be quantified relative to existing abundance and environmental conditions. Laboratory studies will be used to isolate confounding variables such as effects of temperature and turbidity on predation vulnerability and to quantify relative predation impacts of channel catfish, common carp, fathead minnow and plains killifish on humpback chub eggs and larvae and juveniles under conditions present in the LCR. Field evaluations of catfish diets will be used in conjunction with relative abundance data to model population level impacts of these warm-water invasive fish on humpback chub within the LCR. Combining laboratory studies, field studies, monitoring efforts, and modeling will allow researchers to understand how predation by existing invasive warm-water fish and predation by new invasive species may impact humpback chub at various life stages and at a population level. This will allow managers to improve decisions about management actions designed to conserve Colorado River native fish and ensure that any future management actions that are undertaken are focused only on only those fish that are actually having the most detrimental impacts on native fish populations.

5.2. Deliverables

This work will result in an annual report on the status and trends of the fish community in the CRe to be presented to the GCDAMP at their annual reporting meetings. In addition we will provide data as needed at TWG and AMWG meetings in support of decisions related to actions proposed by resource management agencies. Peer reviewed journal articles will also be submitted for publication in FY20, which will detail the results of the eDNA evaluation, the Asian tapeworm monitoring, and the potential risks that warm-water nonnative fish pose to native fish in the Little Colorado River.

6. References

Carim, K.J., McKelvey, K.S., Young, M.K., Wilcox, T.M., and Schwartz, M.K., 2016, A protocol for collecting environmental DNA samples from streams: Fort Collins, Colo., U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General technical report RMRS-STR-355, 18 p., https://www.treesearch.fs.fed.us/pubs/52466.

Clarkson, R.W., Marsh, P.C., Stefferud, S.E., and Stefferud, J.A., 2005, Conflicts between native fish and nonnative sport fish management in the southwestern United States: Fisheries, v. 30, no. 9, p. 20-27, http://dx.doi.org/10.1577/1548-8446(2005)30[20:CBNFAN]2.0.CO;2.

Cucherousset, J., and Olden, J.D., 2011, Ecological impacts of nonnative freshwater fishes: Fisheries, v. 36, no. 5, p. 215-230, http://dx.doi.org/10.1080/03632415.2011.574578.

Pilliod, D.S., Goldberg, C.S., Arkle, R.S., and Waits, L.P., 2013, Estimating occupancy and abundance of stream amphibians using environmental DNA from filtered water samples: Canadian Journal of Fisheries and Aquatic Sciences, v. 70, no. 8, p. 1123-1130, http://dx.doi.org/10.1139/cjfas-2013-0047.

Dawson, V.K., and Kolar, C.S., eds., 2003, Integrated management techniques to control nonnative fishes—completion report: La Crosse, Wisc., prepared for the Bureau of Reclamation by U.S. Geological Survey, Upper Midwest Environmental Sciences Center, 146 p. plus appendices, https://www.umesc.usgs.gov/documents/reports/2003/bor_final_report.pdf.

Dodds, W.K., Robinson, C.T., Gaiser, E.E., Hansen, G.J.A., Powell, H., Smith, J.M., Morse, N.B., Johnson, S.L., Gregory, S.V., Bell, T., Kratz, T.K., and McDowell, W.H., 2012, Surprises and insights from long-term aquatic data sets and experiments: BioScience, v. 62, no. 8, p. 709-721, https://doi.org/10.1525/bio.2012.62.8.4.

Ficetola, G.F., Miaud, C., Pompanon, F., and Taberlet, P., 2008, Species detection using environmental DNA from water samples: Biology Letters, v. 4, no. 4, p. 423-425, http://rsbl.royalsocietypublishing.org/content/4/4/423.

Goldberg, C.S., Pilliod, D.S., Arkle, R.S., and Waits, L., 2011, Molecular detection of vertebrates in stream water—A demonstration using Rocky Mountain tailed frogs and Idaho giant salamanders: PLoS ONE, v. 6, no. 7, e22746, p. 1-5, https://doi.org/10.1371/journal.pone.0022746.

Haden, G.A., 1992, Nonnative fishes of the Grand Canyon, Arizona—A review with regards to their effects on native fishes: Flagstaff, Ariz., Bureau of Reclamation, Glen Canyon Environmental Studies, 29 p., http://www.nativefishlab.net/library/textpdf/20950.pdf.

Hilwig, K.D., and Andersen, M.E., 2011, Summary of nonnative fish control options, monitoring strategies, and research needs for Grand Canyon, Arizon: Flagstaff, Ariz., U.S. Geological Survey unpublished Administrative Report, Grand Canyon Monitoring and Research Center, 104 p.

Hoffman, G.L., and Schubert, G., 1984, Some parasites of exotic fishes, *in* Courtenay, W.R.J., and Stauffer, J.R.J., eds., Distribution, biology, and management of exotic fishes: Baltimore, Md., Johns Hopkins University Press, p. 233-261.

Johnson, B.M., Arlinghaus, R., and Martinez, P.J., 2009, Are we doing all we can to stem the tide of illegal fish stocking?: Fisheries, v. 34, no. 8, p. 389-394, http://dx.doi.org/10.1577/1548-8446-34.8.389.

Klymus, K.E., Richter, C.A., Chapman, D.C., and Paukert, C., 2015, Quantification of eDNA shedding rates from invasive bighead carp *Hypophthalmichthys nobilis* and silver carp

Hypophthalmichthys molitrix: Biological Conservation, v. 183, p. 77-84, https://doi.org/10.1016/j.biocon.2014.11.020.

Leung, B., Lodge, D.M., Finnoff, D., Shogren, J.F., Lewis, M.A., and Lamberti, G., 2002, An ounce of prevention or a pound of cure—Bioeconomic risk analysis of invasive species: Proceedings of the Royal Society B—Biological Sciences, v. 269, no. 1508, p. 2407-2413, http://dx.doi.org/10.1098/rspb.2002.2179.

Lindenmayer, D.B., Likens, G.E., Krebs, C.J., and Hobbs, R.J., 2010, Improved probability of detection of ecological “surprises”: Proceedings of the National Academy of Sciences, v. 170, no. 51, p. 21957–21962, http://dx.doi.org/10.1073/pnas.1015696107.

Marsh, P.C., and Pacey, C.A., 2005, Immiscibility of native and non-native fishes, *in* Brouder, M.J., Springer, C.L., and Leon, C.S., eds., Restoring natural function within a modified riverine environment—the lower Colorado River, Albuquerque, N.Mex., July 8-9, 1998 and *in* Restoring native fish to the lower Colorado River—Interactions of native and non-native fishes, Las Vegas, Nev., July 13-14, 1999, Proceedings of two symposia: p. 59-63.

Martinez, P., Wilson, K., Cavalli, P., Crockett, H., Speas, D.W., Trammell, M., Albrecht, B., and Ryden, D., 2014, Upper Colorado River Basin nonnative and invasive aquatic species prevention and control strategy—final report: Lakewood, Colo., U.S. Fish and Wildlife Service Upper Colorado River Endangered Fish Recovery Program, 125 p., http://www.coloradoriverrecovery.org/general-information/program-elements/nna/BASINWIDENNFSTRATEGYFeb2014.pdf.

McIntosh, C.R., Shogren, J.F., and Finnoff, D.C., 2010, Invasive species and delaying the inevitable—Valuation evidence from a national survey: Ecological Economics, v. 69, no. 3, p. 632-640, https://doi.org/10.1016/j.ecolecon.2009.09.014.

Melis, T.S., Walters, C.J., and Korman, J., 2015, Surprise and opportunity for learning in Grand Canyon—The Glen Canyon Dam adaptive management program: Ecology and Society, v. 20, no. 3, article 22, available at http://dx.doi.org/10.5751/ES-07621-200322.

Meretsky, V.J., Valdez, R.A., Douglas, M.E., Brouder, M.J., Gorman, O.T., and Marsh, P.C., 2000, Spatiotemporal variation in length-weight relationships of endangered humpback chub—Implications for conservation and management: Transactions of the American Fisheries Society, v. 129, no. 2, p. 419-428, http://dx.doi.org/10.1577/1548-8659(2000)129<0419:SVILWR>2.0.CO;2.

Minckley, W.L., and Douglas, M.E., 1991, Discovery and extinction of western fishes—A blink of the eye in geologic time, *in* Minckley, W.L., and Deacon, J.E., eds., Battle against extinction—Native fish management in the American West: Tucson, University of Arizona Press, p. 7-17.

Minckley, C.O., 1996, Observations on the biology of the humpback chub in the Colorado River Basin, 1980-1990: Flagstaff, Northern Arizona University, Ph.D. dissertation, 218 p.

Minckley, W.L., and Marsh, P.C., 2009, Inland fishes of the greater southwest—Chronicle of a vanishing biota: Tucson, University of Arizona Press, 426 p.

Mueller, G.A., 2005, Predatory fish removal and native fish recovery in the Colorado River mainstem—What have we learned?: Fisheries, v. 30, no. 9, p. 10-19, http://dx.doi.org/10.1577/1548-8446(2005)30[10:PFRANF]2.0.CO;2.

Pimentel, D., Lach, L., Zuniga, R., and Morrison, D., 2000, Environmental and economic costs of nonindigenous species in the United States: BioScience, v. 50, no. 1, p. 53-65, https://doi.org/10.1641/0006-3568(2000)050[0053:EAECON]2.3.CO;2.

Schäperclaus, W., 1986, Fish diseases—Vol. 2: Berlin, Germany, Akademie-Verlag.
Speas, D.W., Walters, C.J., Ward, D.L., and Rogers, R.S., 2004, Effects of intraspecific density and environmental variables on electrofishing catchability of brown and rainbow trout in the Colorado River, Arizona: North American Journal of Fisheries Management, v. 24, no. 2, p. 586-596, http://dx.doi.org/10.1577/M02-193.1.
Strickler, K.M., Fremier, A.K., and Goldberg, C.S., 2015, Quantifying effects of UV-B, temperature, and pH on eDNA degradation in aquatic microcosms: Biological Conservation—Special Issue—Environmental DNA, v. 183, p. 85-92, https://doi.org/10.1016/j.biocon.2014.11.038.
U.S. Fish and Wildlife Service, 2002, Humpback chub *(Gila cypha)* recovery goals—Amendment and supplement to the humpback chub recovery plan: Denver, Colo., U.S. Fish and Wildlife Service, Mountain Prairie Region 6, 71 p., http://www.fwspubs.org/doi/suppl/10.3996/102015-JFWM-101/suppl_file/10.3996_102015-jfwm-101.1.s6.pdf?code=ufws-site.
U.S. Department of Interior, 2016, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.
Vernieu, W.S., Hueftle, S.J., and Gloss, S.P., 2005, Water quality in Lake Powell and the Colorado River, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon—A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 69-85 p., http://pubs.usgs.gov/circ/1282/.
Ward, D.L., 2007, Removal and quantification of Asian tapeworm from bonytail chub using Praziquantel: North American Journal of Aquaculture, v. 69, no. 3, p. 207-210, http://dx.doi.org/10.1577/A06-054.1.
Walters, C.J., 1986, Adaptive management of renewable resources: Caldwell, N.J., The Blackburn Press.

7. Budget

		Fiscal Year 2018							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***								
I.1	System-wide native fish and invasive aquatic species monitoring	$58,115	$500	$2,000	$71,255	$210,000		$26,815	$368,685
I.2	Improve early detection of warm-water invasive fish	$9,769			$9,732	$21,000		$3,664	$44,165
I.3	Assess the risks warm-water nonnative fish pose to native fish	$103,821	$1,000	$20,000				$19,418	$144,239
	Total I	**$171,706**	**$1,500**	**$22,000**	**$80,987**	**$231,000**	**$0**	**$49,897**	**$557,090**

		Fiscal Year 2019							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***								
I.1	System-wide native fish and invasive aquatic species monitoring	$38,449	$500		$80,665	$210,000		$37,400	$367,014
I.2	Improve early detection of warm-water invasive fish	$10,062	$1,000	$200	$10,872	$27,500		$6,580	$56,214
I.3	Assess the risks warm-water nonnative fish pose to native fish	$102,452	$1,000	$22,000				$32,618	$158,070
	Total I	**$150,964**	**$2,500**	**$22,200**	**$91,537**	**$237,500**	**$0**	**$76,597**	**$581,299**

		Fiscal Year 2020							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***								
I.1	System-wide native fish and invasive aquatic species monitoring	$39,602	$500		$83,160	$210,000		$38,348	$371,610
I.2	Improve early detection of warm-water invasive fish	$10,364	$1,000		$11,472	$21,000		$6,567	$50,403
I.3	Assess the risks warm-water nonnative fish pose to native fish	$100,281	$1,000	$22,000				$32,053	$155,334
	Total I	**$150,247**	**$2,500**	**$22,000**	**$94,632**	**$231,000**	**$0**	**$76,969**	**$577,347**

Project J. Socioeconomic Research in the Colorado River Ecosystem

1. Investigators

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2. Project Summary

Project J is designed to identify preferences for, and economic values of, downstream resources and evaluate how these metrics are influenced by GCD operations, including proposed experiments in the GCD LTEMP EIS (U.S. Department of Interior, 2016a). The research will also integrate economic information from the project with data and predictive models from long-term and ongoing physical and biological monitoring and research studies led by the GCMRC to develop integrated assessment models (multidisciplinary models [e.g., biology and hydropower] that incorporate social and economic considerations), improving the ability of the GCDAMP resource managers and stakeholders to evaluate and prioritize management actions, monitoring and research.

This project involves two related socioeconomic research elements. These elements build on research in the FY2015-17 TWP (Bureau of Reclamation and U.S. Geological Survey, 2014) and include: a) implementation of a tribal member population survey to assess preference for and value of downstream resources (Element 1); and b) development and integration of decision support models, using economic metrics, to evaluate and prioritize monitoring of, and research on, resources downstream of GCD, including the anticipated success (or lack thereof) of proposed experiments in the LTEMP EIS (Element 2). As detailed in the Proposed Work section of this project, Element 2 would prioritize modeling of resources with the highest priority for protection, resource that are impacted by operational decisions at GCD, and resources that have sufficient predictive modeling frameworks developed to assess future resource states. Priority for research is based on resources for which protection is required under law (e.g., Endangered Species Act), exhibit relatively large economic value, and garner a significant portion of the GCMRC annual budget.

Element 1:

The proposed quantitative population-level tribal research is designed to provide an efficient and timely approach to assessing tribal values, perspectives and knowledge of CRe resources. The tribal member population surveys would apply a set of standard methods extensively used in resource economics studies for valuing ecosystem services. The research would inform on tribal perspectives (e.g., perspectives on management actions) and preferences for trade-offs (e.g., tradeoffs between energy generation and other downstream resources) related to operation of GCD. This information is critical when developing quantitative adaptive management models that assess the most cost-effective management actions and value of reducing scientific uncertainty (e.g., Element 2). This project element would build on the qualitative research in Project 13.2 in the FY2015-17 TWP. The qualitative research in FY2017 is being accomplished through workshops with tribes involved in the GCDAMP, coordinated with recent work, including a NPS nonuse survey focused on national and regional populations (Duffield and others, 2016), as well as direct use recreation studies (Bair and others, 2016; Neher and others, revise and resubmit; Bureau of Reclamation and U.S. Geological Survey, 2014). This work is scheduled to be completed prior to implementation of Element 1.

Element 2:

This project element will build on the framework of a bioeconomic model developed to integrate rainbow trout and humpback chub population models and cost-effectiveness analysis, used to identify efficient management actions to meet adult humpback chub abundance goals (Bureau of Reclamation and U.S. Geological Survey, 2014). Current research includes the exploration of which uncertainties in humpback chub population parameters have the greatest implications for management decisions (i.e., quantitative adaptive management model) and the explicit trade-offs (efficacy and cost) between TMFs and rainbow trout removals at the LCR. Element 2 will explore which drivers, linkages and uncertainties in experimental flows (e.g., TMFs) have the greatest implications for rainbow trout management decisions, and address the impacts of long-term trends in recruitment of rainbow trout and humpback chub of rainbow trout and humpback chub on monitoring and research priorities. Integrating hydropower analysis into the modeling of TMFs will be a primary focus of Element 2. Hydropower analysis is an incremental step in the development of applied decision and scenario analysis research at GCMRC. Adding hydropower analysis into the applied decision and scenario analysis research is timely provided the proposed LTEMP EIS experiments, including TMFs.

Element 1 addresses the LTEMP ROD objective to respect the "interests and perspectives of American Indian Tribes" and Element 2 addresses the LTEMP ROD objective to "determine the appropriate experimental framework that allows for a range of programs and actions, including ongoing and necessary research, monitoring, studies, and management actions in keeping with the adaptive management process" (U.S Department of Interior, 2016b). Element 2 also considers hydropower and attempts to "maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term stability of downstream resources" (U.S. Department of Interior, 2016b). Element 2's focus on adaptive management modeling is consistent with the GCDAMP fisheries review panel's recommendation that the program, "adopt [a] decision theoretic approach to adaptively manage the rainbow trout fishery and humpback chub population" (Casper and others, 2016). A decision-theoretic approach to adaptive management is when a, "predictive model or set of models are created that represent alternative ideas of how the system works" and those priors are evaluated through predicted or actual future resource states (Casper and others, 2016). This approach, would allow the GCDAMP to "optimize" monitoring and research by identifying the relative efficiency of learning opportunities. The proposed project elements therefore address the LTEMP EIS resource goals related to humpback chub, tribal concerns, hydropower, and rainbow trout.

3. Hypotheses and Science Questions

Hypotheses in Element 1:

- Tribal member preferences for and values of downstream resources differ among resource attributes.
- Tribal member preferences for and values of downstream resources differ among tribes and the general population.

Hypotheses in Element 2:

- Mitigation of the effects of rainbow trout on humpback chub through flow actions are more cost-effective in the long-run relative to non-native removal efforts in the LCR reaches.
- Flow actions that improve and support the long-term stability of downstream resources are also able to maintain or improve the value of hydropower generation at GCD.

4. Background

Project J would meet critical socioeconomic information needs identified by the GCDAMP (AMWG, 2012a). Furthermore, the implementation of proposed experiments in the LTEMP EIS are, "contingent on the responses of one or more socioeconomic metrics" (VanderKooi and others, 2017). These metrics include the status and trade-offs associated with resources of Tribal importance because operation of GCD also has direct effect on downstream resources of cultural value and traditional use in GLCA and GCNP. The GCPA of 1992 states that, "…monitoring programs and activities conducted under subsection (a) shall be established and implemented in consultation with…tribes…" (GCPA, sec. 1805(c)). Therefore, measures of resource status or health and appropriate management will need to be determined individually by the federal agencies in consultation with the tribes (AMWG, 2012b). Element 1 addresses this need and, in coordination with the tribes, is critical for furthering the understanding of tribal preferences for, and socioeconomic impacts associated with, resource management decisions, including the proposed and ongoing experiments identified in the LTEMP EIS (U.S. Department of Interior, 2016a).

The role of the GCMRC, and cooperators, is to provide information on physical and biological resources while also providing information related to socioeconomic aspects of resources (VanderKooi and others, 2017). Element 2 will focus on development of a set of integrated assessment models, utilizing research at GCMRC and in the LTEMP EIS, to formally model tradeoffs and prioritize monitoring and research. This is important because it is the "absence of decision making mechanisms" in adaptive management programs that make systematic prioritization of investment in monitoring, research, and management alternatives difficult (Scarlet, 2013). Including economic assessment of investment in monitoring and research is an important component of such programs (Doremus, 2010). While previous research has developed a decision support system for the CRe in GLCA and GCNP downstream from GCD, modeling of management scenarios of other resources (e.g., sediment storage, native fish) were very uncertain due to limited empirical data (Walters and others, 2000). Utilizing ongoing biological research by GCMRC and cooperators, Element 2 will continue to improve the GCDAMP's ability to prioritize research, including evaluating proposed experiments and actions identified in the LTEMP EIS (U.S. Department of Interior, 2016a).

5. Proposed Work

5.1. Project Elements

Project Element J.1. Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey

Lucas Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
John Duffield, Adjunct Research Professor, University of Montana

The objective of Element 1 is to identify tribal member preferences and values associated with management of resources downstream of GCD, through a tribal member population survey, in order to inform decision making processes in the GCDAMP. Defining individual tribe's preferred actions and perspectives associated with management of downstream resources is important when evaluating potential actions and developing adaptive management models that prioritize monitoring and research. Emphasis will be placed on resources of tribal significance that are affected by dam operations and flow experiments in the LTEMP EIS. The assessment of tribal preferences and values will be achieved through in-person interviews with tribal members, using choice experiment methods to explicitly evaluate management actions and tradeoffs between resource attributes. The project will be implemented in FY2018, conditional on successful completion of Project 13.2 in the FY2015-17 TWP, and coordinated with other tribal related studies, including the Bureau of Reclamation's Tribal Associated Values Studies project (see Chapter 1).

Hypotheses in Element 1 include:

- Tribal member preferences for and values of downstream resources differ among resource attributes.
- Tribal member preferences for and values of downstream resources differ among tribes and the general population.

To test these hypotheses, the tribal preference relationships among resource attributes (e.g., hydropower, native fish, sediment, rainbow trout fishery) will be generated and assessed. These hypotheses posit that there will be significant variation in each tribes' preferences for and values of downstream resources by resource attribute and significant differences across tribes and with the general public. This research will enhance understanding of tribal preferences for and values of downstream resources, and is critical in development of formal adaptive management models in Element 2, prioritizing monitoring and research decisions within the GCDAMP.

The efficient way to undertake Tribal research will be to build on the comprehensive NPS national and regional non-use survey and past examples of published stated preference surveys with indigenous populations (Adamowicz and others, 1998; Gonzalez-Caban and others, 2006; Duffield and others, 2016). The NPS non-use value survey was completed for purposes of informing planning and management needs. Where applicable, the proposed tribal socioeconomic tasks are to build on (and benefit from) the larger NPS effort. The NPS study sampled Native Americans, but only in proportion to their presence in the national and regional populations, which resulted in too small a sample size (particularly for the subset of just GCDAMP tribes) for interpretation, necessitating the tribal member sample in Element 1. Where appropriate, the tribal surveys will utilize the general NPS survey layout, choice experiment format, and attitudinal questions.

The population surveys would expand on the qualitative effort in Project Element 13.2 in the FY2015-17 TWP and use a set of resource valuation tools that are extensively used in resource economics studies used for valuing ecosystem services. Similarly, these tools and their applications have been previously reviewed in the context of both direct recreation and non-use values for Colorado River related studies (Welsh and others, 1995; Bair and others, 2016; Neher and others, revise and resubmit). With respect to nonuse, only stated preference measures are feasible, and for purposes of this tribal socioeconomic study choice experiments would be used. The choice experiment method is a widely utilized approach in resource valuation and is the specific approach utilized in the NPS non-use valuation study (Duffield and others, 2016) for purposes of the Final LTEMP EIS (U.S. Department of Interior, 2016a).

For the choice experiment methods, downstream resource attributes of tribal importance (e.g., hydropower, native fish) and their potential variation with different future management actions will be defined and will shape the experimental design. The experimental design will be based on the number of attributes and future scenarios defined in Project 13.2 in the FY2015-17 TWP. It is important to note that comparisons among resource attributes can contain explicit cost information (e.g., forgone hydropower benefits) when comparing future resource attributes. 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 attributes and the rates of substitution between resource attribute tradeoffs.

Implementation of the tribal population surveys would include a sample frame of registered tribal members and a total of at least 2,000 potential respondents, across all tribes, who would be randomly selected. Alternatively, survey respondents may be randomly chosen from a subset of individuals (e.g., Navajo chapter meetings) or identified through consultation with tribal councils and government agencies (e.g., Hopi clans) to collect a representative sample from various segments of the tribe. Surveys would be implemented using an in-person survey format. It will be necessary to undertake a separate survey of non-respondents, those who were asked to take the survey and did not, in order to meet the standards for a scientifically valid population survey. The non-response survey will be conducted in-person and will focus on collecting data on demographics and a subset of the survey questions. The target non-response sample is 60 from each participating tribe. Individual participant's anonymity will be protected, as required by the Office of Management and Budget, and the scientific integrity of the research is concomitant with the scientific peer review process. The availability and archival of survey data will be determined in consultation with individual tribes.

Project Element 1 will be implemented in cooperation with tribal leadership, including representatives to the TWG and tribal staff who will collaborate on research activities (e.g., survey implementation and scientific presentation and publication) and assist in overcoming language and cultural barriers. Many of the tribal representatives to the TWG and tribal staff are trained anthropologists who have worked with the tribes in adaptive management of Colorado River resources over several decades. Outside expertise in cultural anthropology for interpretation of survey results will be sought as deemed necessary by the tribes. Funding will be available to tribal staff and survey participants, as appropriate, to achieve successful collaboration and project completion.

Results of Element 1 are critical in informing decisions in the GCDAMP. Specifically, the results of Element 1 will inform quantitative adaptive management model development and improve the ability of the GCDAMP to prioritize monitoring and research in an effort to meet desired future conditions while considering various perspectives of stakeholders. For example, constraining management actions that stakeholders find objectionable (e.g., mechanical removal of rainbow trout) in a quantitative adaptive management model allows researchers to test alternative hypotheses about population dynamics and assess the importance of various monitoring and research efforts (e.g., reducing uncertainty in humpback chub recruitment) to improve management of downstream resources while accounting for management preferences of stakeholders. Results from Element 1 will be incorporated into ongoing modeling in Element 2.

Project Element J.2. Applied decision and scenario analysis

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Mathew Reimer, Associate Professor, University of Alaska
Michael Springborn, Assistant Professor, University of California at Davis
Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objective of this project element is to improve the GCDAMP's ability to consider, organize and prioritize monitoring, research, and long-term management related to the operation of GCD, including proposed experiments in the LTEMP EIS. To accomplish this, project Element 2 will build on the framework of a simulation model developed to evaluate cost-effective rainbow trout management strategies in relation to humpback chub population goals and current research addressing critical uncertainties in humpback chub population parameters as well as trade-offs between TMFs and rainbow trout removals (Bureau of Reclamation and U.S. Geological Survey, 2014). 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 resources when considering the need for collaboration, complex biophysical/socioeconomic interactions, and stakeholder perspectives (including results of Element 1). This project element will be coordinated with monitoring and research in humpback chub and salmonid related projects. Charles Yackulic, a co-principal investigator on this project element, leads or is involved with all of the fisheries related projects in this work plan.

The Non-native Fish Control Downstream from GCD Environmental Assessment (Reclamation, 2011), informally hypothesizes that mitigation of the effects of rainbow trout on humpback chub through flow actions may be more cost-effective in the long-run relative to the proposed non-native removal efforts in the LCR reaches (Reclamation, 2011). This is the type of hypothesis that is addressed in current research (Bureau of Reclamation and U.S. Geological Survey, 2014). Element 2 will further address how LTEMP EIS experiments (e.g., active learning with respect to TMFs) and future trends in rainbow trout and humpback chub recruitment can be used to further refine and test this hypothesis (e.g., passive learning with respect to long-term trends in hydrology).

Analytical model development of downstream resources in support of adaptive management has been prioritized in past work plans, based on resources that exhibit significant economic value and/or that garner a significant portion of the GCMRC annual budget, are impacted by operational decisions at GCD, and have sufficient predictive modeling frameworks developed to assess future resource states (Bureau of Reclamation and U.S. Geological Survey, 2014). The initial focus of Element 2 will be to develop methods to identify the importance of monitoring and research with respect to LTEMP EIS experiments (e.g., TMFs). When considering the economic value of reducing uncertainty through monitoring and research, it is important to consider the short-run costs associated with experimentation relative to long-run benefits of meeting resource goals. In the case of TMFs, in coordination with Project N, evaluation of experimental designs to benefit both biological and hydropower resources will be undertaken, while incorporating the total value of hydropower , will be formally considered when evaluating flow experiments, rainbow trout removal and humpback chub recovery goals. This model development will combine the decision frameworks established to formally assess the cost-effective approach to TMFs and rainbow trout removal and formal adaptive management modeling (e.g., identifying the relative importance of reducing uncertainty through monitoring and research to improve resource management) (Bureau of Reclamation and U.S. Geological Survey, 2014). A workshop will occur with GCMRC staff and GCDAMP stakeholders in fiscal year 2018 to review and discusses the trade-offs between TMFs, expected downstream rainbow trout and humpback chub outcomes and associated economic implications of management actions, including hydropower. This workshop will provide an opportunity to explore opportunities to improve hydropower resources while meeting downstream rainbow trout and humpback chub resources goals as defined in the LTEMP EIS (U.S. Department of Interior, 2016a).

As with previous modeling efforts (Bureau of Reclamation and U.S. Geological Survey, 2014) the proposed model development 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 USFWS (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 qualities of cost-effectiveness analysis that 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 (Bureau of Reclamation and U.S. Geological Survey, 2014).

While the initial task is focused on research to identify the "optimal' learning with respect to flow experiments (e.g., TMFs), the modeling effort will include an evaluation of the importance of variation in rainbow trout and humpback cub recruitment under changing environmental conditions. This additional task includes incorporating long-run trends in rainbow trout and humpback chub recruitment into models that consider the "optimal" learning that occurs with rainbow trout management experiments (e.g., TMFs). This approach accounts for non-stationary dynamics in natural systems (e.g., hydrology) by incorporating passive learning (Nicol and others, 2015), in parallel with active learning (i.e., LTEMP EIS experiments), to improve the ability to prioritize monitoring and research opportunities.

Integrated assessment models will be developed in cooperation with stakeholders, according to needs in evaluating LTEMP EIS experiments and the advancement of scientific knowledge at GCMRC. 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. Results of Element 2 are essential in enabling the GCDAMP to better organize and evaluate the scientific monitoring and research results provided by GCMRC.

5.2. 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 Element 1 will be provided to individual tribes as requested.

- In FY2018–20, two manuscripts will be prepared from the results of Project Element J.1 for submission to peer-reviewed scientific journals.
- In FY2018–20, two manuscripts will be prepared from the results of Project Element J.2 for submission to peer-reviewed scientific journals.

6. Elements and Activities Proposed, but not Included in the Final Work Plan

Project Element J.(i).

The purpose of this project component is to build on the research accomplished in Project 13.1 in the TWP FY2015-17. This includes utilizing the economic values identified with Grand Canyon whitewater boating and Glen Canyon angling to expand on a scenario analysis model developed for the LTEMP EIS, to estimate the net economic value of whitewater boating and angling under various flow scenarios including experimental flows considered in the LTEMP EIS. This modeling would incorporate up-to-date economic value information estimated for Project 13.1 in the TWP FY2015-17. Simulation models and visualization tools to evaluate experimental flows and other management actions will be developed in a web-based platform and hosted by GCMRC. The project would also develop a regional economic impact model of Glen Canyon angling, utilizing settings from the recreational experience scenario analysis model. The regional economic impact model would allow for an assessment of the regional economic impacts of variation in guided and non-guided angler participation in Glen Canyon. The model would rely on angler expenditure data collected in the angler surveys administered for Project 13.1 in the TWP FY2015-17. The project element would also implement a Grand Canyon whitewater guide (i.e., commercial whitewater guides) survey to identify and evaluate key recreational experience attributes that may differ under alternative flow regimes and events such as HFEs, low steady flows and other experiments in the LTEMP EIS. This survey would allow the GCDAMP to better understand impacts to the whitewater recreational experience, building on the economic surveys in Project 13.1 in the TWP FY2015-17.

7. References

Adamowicz , W., Beckley, T., Hatton Macdonald, D., Just, L., Luckert, M., Murray, E., and Phillips, W., 1998, In search of forest resource values of indigenous peoples—Are nonmarket valuation techniques applicable?: Society & Natural Resources—An International Journal, v. 11, no. 1, p. 51-66, http://dx.doi.org/10.1080/08941929809381061.

Bair, L.S., Rogowski, D.L., and Neher, C., 2016, Economic value of angling on the Colorado River at Lees Ferry—Using secondary data to estimate the influence of seasonality: North American Journal of Fisheries Management, v. 36, no. 6, p. 1229-1239, http://dx.doi.org/10.1080/02755947.2016.1204388.

Baxter, P.W.J., Sabo, J.L., Wilcox, C., McCarthy, M.A., and Possingham, H.P., 2008, Cost-effective suppression and eradication of invasive predators: Conservation Biology, v. 22, no. 1, p. 89-98, http://www.jstor.org/stable/20183348.

Bureau of Reclamation, 2011, Environmental Assessment—Non-native fish control downstream from Glen Canyon Dam: Salt Lake City, Utah, Department of the Interior, Bureau of Reclamation, 112 p. plus appendices, https://www.usbr.gov/uc/envdocs/ea/gc/nnfc/NNFC-EA.pdf.

Bureau of Reclamation, and U.S. Geological Survey, 2014, Glen Canyon Adaptive Management Program triennial budget and work plan—Fiscal years 2015-2017: Bureau of Reclamation, Upper Colorado Regional Office and U.S. Geological Survey, Grand Canyon Monitoring and Research Center, prepared in conjunction with the Glen Canyon Dam Adaptive Management Program, 475 p. plus appendices, https://www.usbr.gov/uc/rm/amp/amwg/mtgs/14aug27/Attach_06f.pdf.

Casper, A., Jackson, D., Gido, K.B., Peterson, J., and Rahel, F.J., 2016, Final report for the Fisheries Program Review (PEP): Glen Canyon Dam Adaptive Management Program (GCDAMP) Protocols Evaluation Panel, 33 p., http://gcdamp.com/images_gcdamp_com/8/80/Fisheries_PEP_Report_2016-12-27.pdf.

Doremus, H., 2010, Adaptive management as an information problem: NCL Review, v. 89, p. 1455, http://scholarship.law.berkeley.edu/facpubs/1672/.

Duffield, J., Neher, C., and Patterson, D., 2016, Colorado River total value study—final report: Missoula, University of Montana, Dept. of Mathematical Sciences, prepared for National Park Service, 79 p. plus appendices, http://ltempeis.anl.gov/documents/docs/Colorado_River_Value_Study.pdf.

Glen Canyon Dam Adaptive Management Work Group (AMWG), 2012a, Recommended information needs and program elements for a proposed AMP socioeconomics program as approved by AMWG on February 23, 2012: Phoenix, Ariz., AMWG, https://www.usbr.gov/uc/rm/amp/amwg/mtgs/12feb22/Attach_07b.pdf.

Glen Canyon Dam Adaptive Management Work Group (AMWG), 2012, Desired future conditions for the Colorado River ecosystem in relation to Glen Canyon Dam: DFC Ad Hoc Committee Review as approved by AMWG on February 23, 2012, 34 p., https://www.usbr.gov/uc/rm/amp/amwg/mtgs/12feb22/Attach_04.pdf.

Gloss, S., Lovich, J.E., and Melis, T.S., eds., 2005, The state of the Colorado River ecosystem in Grand Canyon: A report of the Grand Canyon Monitoring and Research Center 1991-2004: U.S. Geological Survey Circular 1282, 220 p., http://pubs.usgs.gov/circ/1282/.

González-Cabán, A., Loomis, J.B., Rodriguez, A., and Hesseln, H., 2007, A comparison of CVM survey response rates, protests and willingness-to-pay of Native Americans and general population for fuels reduction policies: Journal of Forest Economics, v. 13, no. 1, p. 49-71, https://doi.org/10.1016/j.jfe.2006.10.001.

Nicol, S., Fuller, R.A., Iwamura, T., and Chadès, I., 2015, Adapting environmental management to uncertain but inevitable change: Proceedings of the Royal Society B—Biological Sciences, v. 282, no. 1808, p. 1-8, http://dx.doi.org/10.1098/rspb.2014.2984.

Neher, C., Duffield, J., Bair, L.S., Patterson, D., and Neher, K., *revised and resubmitted*, Testing the limits of temporal stability—Willingness to pay values among Grand Canyon whitewater boaters across decades: Water Resource Research.

Scarlet, L., 2013, Collaborative adaptive management—Challenges and opportunities: Ecology and Society, v. 18, no. 3, article 26, available at http://dx.doi.org/10.5751/ES-05762-180326.

U.S. Department of the Interior, 1996, Record of Decision—Operation of Glen Canyon Dam Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Glen Canyon Dam Adaptive Management Program, 15 p., http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf.

U.S. Department of Interior, 2016a, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

U.S. Department of Interior, 2016b, Record of decision for the Glen Canyon Dam long-term experimental and management plan final environmental impact statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Fish and Wildlife Service, 2002, Humpback chub *(Gila cypha)* recovery goals—Amendment and supplement to the humpback chub recovery plan: Denver, Colo., U.S. Fish and Wildlife Service, Mountain Prairie Region 6, 71 p., http://www.fwspubs.org/doi/suppl/10.3996/102015-JFWM-101/suppl_file/10.3996_102015-jfwm-101.1.s6.pdf?code=ufws-site.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Yackulic, C.B., Schmidt, J.C., and Sankey, J.B., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

Walters, C., Korman, J., Stevens, L.E., and Gold, B., 2000, Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon: Conservation Ecology, v. 4, no. 2, article 1, available at http://www.consecol.org/vol4/iss2/art1/.

Welsh, M.P., Bishop, R.C., Phillips, M.L., and Baumgartner, R.M., 1995, Glen Canyon Dam Colorado River storage project, Arizona—Non-use values final study summary report: Madison, Wisc., Hagler Bailly Consulting, Inc., National Technical Information Service no. PB98-106636, 37 p.

8. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
J	***Socioeconomic Research in the Colorado River Ecosystem***								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$55,778	$2,500	$600		$71,500		$11,305	$141,683
J.2	Applied decision and scenario analysis	$87,687	$750	$300		$36,000		$14,885	$139,622
	Total J	**$143,465**	**$3,250**	**$900**	**$0**	**$107,500**	**$0**	**$26,189**	**$281,305**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
J	***Socioeconomic Research in the Colorado River Ecosystem***								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$86,177	$2,500	$750		$71,500		$25,396	$186,323
J.2	Applied decision and scenario analysis	$51,115	$750	$375				$13,582	$65,822
	Total J	**$137,292**	**$3,250**	**$1,125**	**$0**	**$71,500**	**$0**	**$38,979**	**$252,145**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
J	***Socioeconomic Research in the Colorado River Ecosystem***								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$88,763	$2,500	$750		$71,500		$26,068	$189,581
J.2	Applied decision and scenario analysis	$53,142	$750	$375				$14,109	$68,376
	Total J	**$141,904**	**$3,250**	**$1,125**	**$0**	**$71,500**	**$0**	**$40,178**	**$257,956**

Project K. Geospatial Science and Technology

1. Investigators

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2. Project Summary

The geospatial and information technology industries continue to change and expand at a rapid pace. Much of this growth is driven by advances in technology—from improved sensors for monitoring the Earth to increased digital data storage capacity to newer computer systems designed for processing large data sets more efficiently to the greater emphasis of the "Internet of Things" where the reliance of web-based technologies have revolutionized our world. The purpose of this project is to continue to advance GCMRC's ability to leverage many of these new technologies for the benefit of the Center, the science projects described within this work plan, and the larger GCDAMP that they serve. Work performed within this project makes it possible to share important information about trends in resources of the CRe to the GCDAMP through web-based, interactive tools and mapping products, allowing the GCDAMP to make informed, time-sensitive decisions on experimental and management actions under the 2016 LTEMP and the associated ROD (U.S. Department of Interior, 2016).

GCMRC continues to collect, store, process, analyze, and serve an ever-growing amount of digital data. Much of the data that now exists in the Center has a geospatial component to it. The importance of being able to effectively manage these data has never been greater as technological advances have increased both the demand and the expectancy of more open data availability. This project will continue to build and maintain systems that will handle these data needs, as well as provide high-level support to other science projects in the form of data processing, data management and documentation, geospatial analysis, and access to the Center's data holdings. Maintaining and improving upon GCMRC's capacity for providing this level of access will be crucial to effective decision-making during the implementation of the LTEMP.

3. Hypotheses and Science Questions

Project K does not address specific science question or hypotheses. However, this project delivers critical support to all work of the GCMRC including services such as data processing, data management and documentation, and geospatial analyses which are essential to the success of all projects.

4. Background

There exists a long legacy of spatial data being collected in support of science focused on studying effects of GCD operations dating back more than 30 years. These data were often disparate between different science projects and certainly between studies focused on different resource types. Only in recent years, with the adoption of more modern GIS and database software, and advancements in data sharing capabilities, has the scope of our research been able to become more integrated across disciplines and among different research efforts.

Data management has been a part of GCMRC since its inception, and was specifically outlined in the 1995 EIS that clearly defines the Center's responsibilities for managing data in support of the GCDAMP (U.S. Department of the Interior, 1995). The concept of data management encompasses many facets including, but not limited to, data preservation, design, development and maintenance of systems and applications designed to store and serve the data, building platforms that provide access to these data, and performing the necessary documentation of data sets. This work was also supported in the 1995 ROD – specifically in GCDAMP Goal 12, to maintain a high-quality monitoring, research and adaptive management program – and in subsequent documents including the most recent LTEMP EIS. During development of the LTEMP, GIS staff were very much involved with data dissemination to the EIS team, and this role will continue throughout the LTEMP implementation process. Success of LTEMP will rely heavily on the GCMRC's ability to continue to disseminate data to stakeholders, managers, and, when appropriate, to the public.

While this project is still adhering to its role as the lead in GIS application to science projects, additional roles have also accumulated as natural extensions to the geospatial science work over the past few years. The functions of data management was previously addressed within the Data Acquisition, Storage, and Analysis (DASA) program, however, since the reorganization of GCMRC in 2013 away from resource programs and towards a new, project-oriented focus, data management responsibilities are no longer centralized for the Center. Because of this reorganization, positions that traditionally focused primarily on GIS support have had to expand their roles to include data management oversight, as well as providing computer systems expertise, web server and internet technology leadership, the design, development and deployment of technologically-advanced scientific monitoring equipment and, most recently, the exploration into cloud-based data and application services. Some of this capacity has existed within GCMRC for more than a decade, but has not to date been sufficiently described within the context of a work plan. The project elements presented in Section 4 of this project proposal describe this increased capacity more fully.

In addition to its commitment to the GCDAMP and LTEMP, the GCMRC, as a part of the USGS, must comply with federal guidelines governing many aspects of how geospatial data are collected and maintained by the Center. These aspects range from how specific data are to be collected, to accuracy standards established through federal policy – Federal Geographic Data Committee (FCDC), National Standard for Spatial Data Accuracy (NSSDA, FGDC, 1998), to how data are to be reviewed and released in conjunction with peer-reviewed scientific publications. This last concept is relatively new and is more fully described by the most recent USGS Fundamental Science Practices in response to an Executive Order that redefined the data release policies of federal agencies (U.S. Geological Survey, 2017). As the Geospatial Science project has increased its role in assisting with proper data management for the Center, work performed in this project will continue to lead efforts for adhering to these requirements.

4.1. Products from current Triennial Work Plan (FY2015-17)

Over the last three years, a concerted effort was made to greatly improve upon GCMRC's online presence, with special attention given to making peer-reviewed data sets and important mapping products made accessible through web-based tools and applications. Additionally, there has been a renewed effort in improving upon the how data are processed and managed within the Center and in direct support of science projects. Both of these aspects (data management and data accessibility) have been greatly improved during FY2015-17, despite having the Geographer position vacant for practically all of FY2016. Below is an outline of products developed by GIS staff that relate to advances in data management performance and online accessibility to data resources. Links are provided for viewing some of these items online.

1) ***Leverage online portals to share geospatial data***
    a. *Hosting GCMRC data via ESRI's ArcGIS online (see Section 6)*
        i. GCMRC GIS staff have worked to build, maintain and periodically update web-based mapping services that provide access to many of the Center's most commonly used GIS data sets.
        ii. URL link: http://www.arcgis.com/home/search.html?q=GCMRC&t=content&restrict=false

    b. *Development and deployment of the Grand Canyon GIS portal*
        i. GCMRC GIS staff have developed its own online GIS Portal designed to share and allow for collaboration on a suite of geospatial resources hosted

by the Center. The portal now contains both commonly used base data such as aerial imagery collected during canyon-wide overflight missions and DEM data sets, as well as project-specific geospatial data including biological information from the citizen science light trap work and the recently published Channel Mapping topography/bathymetry data collected in 2009.

ii. URL link: https://grandcanyon.usgs.gov/portal/home/index.html

2) ***Examples of direct GCDAMP support from GIS staff***

c. *Web applications showing sandbar response to HFEs*

i. Work included the design and implementation of a light-weight, relatively simple process to quickly serve pre- and post-HFE photographs of sandbar sites. Responsible for the development and hosting of HFE-related photo viewing applications for the 2012, 2013, 2014 and 2016 HFEs released from GCD.

ii. Links:

iii. 2016: https://grandcanyon.usgs.gov/gisapps/sandbartour2016/index.html

iv. 2014: https://grandcanyon.usgs.gov/gisapps/sandbartour2014/index.html

v. 2013: https://grandcanyon.usgs.gov/gisapps/sandbartour2013/index.html

vi. 2012: https://grandcanyon.usgs.gov/gisapps/sandbartour2012/index.html

d. *2016 HFE web application showing anticipated inundation areas*

i. Design and implementation of an interactive web mapping application that illustrated anticipated inundation areas in the context of other geographic features (tributaries, rapids, geomorphic features) and other GIS layers (campsites, river miles, day use areas, etc.).

ii. URL link: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=721001c63d91458883340f05c68c55f4

3) ***Recent Project-Specific Work in GIS / Database Development***

e. *Geodetic control network database and application*

i. Designed to standardize both the storage and processing of GNSS and total station surveys. The backend of the application is a SQL Server Express database which provides a central location for data to be stored and retrieved. By standardizing the storage and processing of GNSS and total station data and lessening the reliance on third party software more control is given to GCMRC to organize, visualize, analyze, and share our control network data.

f. Processing of remote sensing GIS derivatives

   i. The physical memory required to process and store GIS derivatives of remote sensing data presents challenges for standard GIS software and disk storage methods. These challenges were overcome by processing and storing the data within a spatially enabled database and building upon the database's built-in functionality. A major benefit of this work is the processing time and storage footprint of the remote sensing derivatives has been greatly reduced leading to a more manageable workflow, data updating model, and data exporting functions.

g. Sandbar database and web application

   i. Updated existing web application and backend database to run within the USGS's Cloud Hosting Solutions. Through this process the serving of sandbar site photos was corrected and improved upon from the previous application and mapping capabilities were updated to utilize the most recent data. This work has provided a model for us moving forward to leverage the cloud hosting and computing power of cloud-based systems. This added functionality will allow us to deliver content through web applications in a more efficient and cost effective manner.

5. Proposed Work

5.1. Project Elements

Project Element K.1. Geospatial data analysis and project support

Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
James Hensleigh, Geographer, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

To measure the amount of GIS support provided to all projects in the FY2018-20 TWP, 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 will be 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. A tentative list of projects that are anticipated to receive this level of support include Sandbar and Sediment Storage (Project B), Riparian vegetation monitoring

(Project C), Humpback chub monitoring (Project G), and Salmonid research (Project H). It is likely that other projects may be added to this list during the on-going planning process.

Outline of high-level support planned:

1) ***Project B. Sandbar and sediment storage***
    a. Serve as internal lead on sandbar database application that has currently been migrated to the USGS Cloud Hosting Solutions platform,
    b. Assist with high-level geoprocessing tasks including channel mapping processing and analysis,
    c. Application development and deployment for larger sandbar repeat photography collection,
    d. Assist with data collection efforts during channel mapping and other field missions.

2) ***Project C. Riparian vegetation monitoring***
    a. Design and develop a riparian vegetation database from current spreadsheets of field collected data,
    b. Streamline data entry process and build in-field computer data entry program, assist with, and
    c. Improve upon current reporting process for determining data collect during site visits and change detection analysis.

3) ***Project G. Humpback chub monitoring***
    a. Continued support for long-term monitoring of humpback chub in the LCR (USFWS), and increased support for newer research conducted by GCMRC in the LCR.
    b. Support for PIT tag antenna array modifications and maintenance in the LCR.
    c. Development of updated fish monitoring system to coincide with the need for more spatial resolute data for hoop net sampling and in previously unsampled reaches of the Colorado River.

Other science projects in the FY2018-20 TWP will likely require some level of support from the Geospatial Information and Technology project, however, this work may not be as intensive—GIS layer development, brief training sessions for staff and cooperators, troubleshooting GIS and other software, data set queries and exporting, and map output generation for publications, presentations and field data collection efforts.

A table is provided in Section 7 listing geospatial science and technology support planned for other science projects. Funding for this element is accounted for in these project budgets.

Project Element K.2. Geospatial data management, processing and documentation

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Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
James Hensleigh, Geographer, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

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 science 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 a relational 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 (Fish Sampling Units, sandbar site and channel mapping topographic surfaces) to more localized reference layers (humpback chub sampling locations in the LCR). Currently, there are two Oracle database servers maintained by GCMRC, one is used for storing all fish sampling information that has been collected through GCDAMP-funded projects, and the other is designed for storing and serving many of GCMRC's geospatial data sets that are used by both internal project staff and through public-facing web applications. The GCMRC Oracle Spatial Database now contains over 2.5 terabytes of geospatial data, with more being added every year.

One major effort for this project element will be the continued development and deployment of an enterprise GIS system for GCMRC. This encompasses all the components of a full geospatial data content delivery system, and has several levels that are further described here. As previously mentioned, GCMRC maintains an Oracle Spatial Database for storing and serving its geospatial data. This will continue to be the case, and there are plans to stand up a separate, new Oracle Spatial Database that will serve first as a development server, but then will also provide the necessary failover required for providing the most consistently available data possible. All of the necessary software and hardware for establishing a second, failover database system currently exist, and now what remains is the time needed to build out this new system. The Oracle Spatial Database is the backbone of our enterprise GIS system, and provides a stable, data-serving platform from which other components of the system will pull from to make the data available.

By the end of FY2017, there will also be an internal ArcGIS Server and Portal server that will provide access to these data through services. Services will exist for much more than just individual data layers. New services will be developed that will allow for better place-name search capabilities, more advanced geospatial analysis tools, and better data downloading and map printing capabilities. This internal, content-serving platform will allow for better collaboration of data between staff in different science projects, and help standardize some data processing and map making workflows for the Center. Additionally, how science staff interact with spatial data will change. Data layers, maps, and geoprocessing functions will be made available through more consistent, web-based workflows, and other desktop applications, such as Microsoft Office, will be able to consume web-based maps directly. This will eliminate the need for basic users of geospatial data to even have GIS software installed on their computers – which in turn reduces costs for equipment and time spent by GIS and information technology staff on installation and troubleshooting tasks. Similarly, custom-designed software and applications may be designed for handling and serving geospatial and other data types that are often unique to the GCMRC, allowing scientists, managers and stakeholders to work with data without requiring specialized software.

Individual science projects currently lack the expertise to sufficiently build and maintain enterprise-level databases and data sets that are necessary products for the GCMRC as the science provider for the AMP. This project will continue to assume a larger role in all aspects of data management for the Center. This work includes consultation with USGS Information Technology (IT) staff at many levels in the organization to ensure the proper systems exist for storage, archiving, retrieval and network access to the data by GCMRC staff. While scientists do currently have some discretion as to how their data are organized and processed, the systems provided are centralized on a modern disk array that has a 250-terabyte capacity and we employ a scheduled, cumulative backup strategy (daily, weekly, monthly) across all accessible network drives. Additionally, we utilize an off-site storage facility to maintain monthly backups for disaster recovery purposes.

This project will also continue to lead the Center in the development of new or improved relational databases that will more efficiently handle scientific data collected by other projects. Several resource areas have been identified as having insufficient capacity for properly storing and maintaining their data in a consistent and logical manner. In some cases, project-related data only exist in simple spreadsheet formats, with no efficient way to compile, analyze, share and provide reporting on specific GCDAMP-funded research efforts. Moving beyond the main focus of geospatial data, this project is poised to further assist with full database development for individual science projects currently lacking relational database support, and that are in dire need of better data storage, analysis, and access capabilities. Additionally, this project will initiate more advanced data processing and computational power through a newly acquired data processing server that leverages server hosted application technology which deploys applications and software from more powerful computer servers to the end users' desktops and laptops. This new processing environment will be designed for advanced geospatial analysis and better performance on model processing conducted by GCMRC scientists.

Members of this project also serve as liaisons to the USGS data review process (Section 3), assist and train staff in metadata development, data management plan creation and adherence, and other work related to the data publication process. Additionally, this project will lead an effort for better implementation of source control procedures for project-based data processing, scripting and program development, software design and development, and development of web-based applications.

Project Element K.3. Access to geospatial data holdings

Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
James Hensleigh, Geographer, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Over the last three years, the GIS team has greatly increased GCMRC's online presence through the ESRI cloud environment, ArcGIS Online (https://www.arcgis.com/), with maps, data layers and applications providing public access to important project-related work. This effort will continue with published data sets, web maps and applications being made available through this online platform. Similarly, this project will lead the Center's effort to use other cloud environments for providing better access to its data and applications. The USGS Cloud Hosting Solutions is part of the USGS cloud environment that will allow for advanced cloud computing, application deployment and access to information through some of the most advanced data serving systems available today. The type of work performed by GCMRC GIS staff involves standardized source control of all application components, advance system configuration of both local desktop and server environments, and the proper deployment and management of Amazon Web Services (AWS)-based components. There are many benefits to leveraging these cloud environments for science applications. They offer scalable resources, many of which only cost the Center while the components are being accessed. The cost of server maintenance, security, data/application availability, storage, and redundancy are all managed by AWS, thus reducing the amount of time needed internally for GIS or information technology staff to perform these duties.

Expanding GMCRC's online presence through cloud environments is only one, albeit a very novel, example of work conducted in this element. This project will continue to add online content for stakeholder and public consumption through custom-built web applications that are hosted on in-house servers. This work will include the continued efforts of maintaining the existing ArcGIS Server and Portal applications currently available through GCMRC's website.

Project Element K.4. Remote monitoring systems and technological engineering

Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element tracks the technical support and electrical engineering expertise provided to other research projects described in this work plan. The type of work performed in this element is varied and must at times adjust to respond to emerging needs within projects. Listed below are specific tasks with individual projects identified, where possible. Some work performed in this element inherently benefits the Center as a whole by improving upon the design and development of common components used by most remote monitoring systems deployed by GCMRC. Due to budgetary constraints and changes made during the TWP planning process, the budget for this element has been eliminated beginning in the second year (FY2019) of the work plan. Going forward, any related needs will be supported by existing project funds.

1) ***Work benefitting the Center***
    a. Design, build, test, deploy, or upgrade field equipment required for field operations; provide capability to implement emerging wireless communications technologies;
    b. Produce software programs to perform machine-to-machine, sensor-to-machine, human-to-machine, and machine-to-cloud communications;
    c. Provide power system design for solar-powered, autonomous field operations; write software programs to maximize automated acquisition and processing of large datasets.
2) ***Project A. Streamflow, water quality, and sediment transport***
    a. Provide technical expertise for communicating with, and controlling GCMRC sediment and water quality monitoring equipment.
    b. Provide radio frequency Wireless and Mobile-to-Mobile communications, Supervisory Control and Data Acquisition (SCADA) hardware and software, power distribution design and implementation.
3) ***Project G. Humpback chub population dynamics***
    a. Provide hardware and software support for the existing LCR PIT-tag antenna array until it reaches end-of-life.
    b. Participate in the development, installation, and maintenance of a new "pinch-point" PIT-tag antenna array.
    c. Perform software installation and hardware integration for the new LCR rim computer.
4) ***Project H. Aquatic ecology and food base monitoring***
    a. Design, build, and maintain a cellular-based SCADA system for aquatic life monitoring in Glen Canyon

5.2. Deliverables

1) Geospatial data sets, metadata documents, and map outputs in various forms in support of other projects.
2) Online web services that include data layers, interactive maps and custom web applications
3) Project-specific relational databases, and associated applications and software for interaction with those databases.
4) Documentation of standardized processes, source control workspaces, wikis, and publications related to these work elements.

6. References

ESRI, 2017, ArcGIS online software, March 2017: Redlands, Calif., Environmental Systems Research Institute, USA, http://www.arcgis.com/home/index.html.

Federal Geographic Data Committee, 1998, Geospatial positioning accuracy standards, part 3—sNational standard for spatial data accuracy—Appendix 3-D—Other accuracy standards: Reston, Va., National Spatial Data Infrastructure, Subcommittee for Base Cartographic Data, report no. FGDC-STD-007.3-1998, 26 p., https://www.fgdc.gov/standards/projects/accuracy/part3/chapter3.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam, Colorado River storage project, Arizona—final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, 337 p. plus appendices, http://www.usbr.gov/uc/envdocs/eis/gc/gcdOpsFEIS.html.

U.S. Department of the Interior, 1996, Record of Decision—Operation of Glen Canyon Dam Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Glen Canyon Dam Adaptive Management Program, 15 p., http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Yackulic, C.B., Schmidt, J.C., and Sankey, J.B., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

U.S. Geological Survey, 2017, Fundamental science practices (FSP)—Policy directives—online manuals: Washington, D.C., Department of the Interior, https://www2.usgs.gov/fsp/policies.asp.

7. Table showing planned geospatial science and technology support to other projects

FY18-20 Work Plan & Budget		Accounting for GIS Services	Time within Proposed Projects		
	FY18-20	FY18-20	FY2018	FY2019	FY2020
Project	Prj.#	GIS Staff	# of Pay Periods	# of Pay Periods	# of Pay Periods
Physical					
Streamflow, Water Quality and Sediment Transport	A	TAndrews, GS-12	1	0	0
Sandbars and Sediment Storage Dynamics	B	JHensleigh, GS-11	4	4	4
Sandbars and Sediment Storage Dynamics	B	TGushue, GS-12	4	4	4
Riparian Vegetation					
Riparian Vegetation Monitoring and Analysis	C	TAndrews, GS-12	1	0	0
Riparian Vegetation Monitoring and Analysis	C	JHensleigh, GS-11	5	2	0
Aquatic Biology					
Aquatic Ecology and Foobase Monitoring	F	TGushue, GS-12	1	1	1
Fisheries					
Humpback chub Pop Dynamics	G	TAndrews, GS-12	2	0	0
Humpback chub Pop Dynamics	G	TGushue, GS-12	1	1	1
Support to other projects		**Subtotals**			
		TGushue Pay Periods	6	6	6
		TAndrews Pay Periods	4	0	0
		JHensleigh Pay Periods	9	6	4

8. Budget

Project	Project Description	Fiscal Year 2018							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
K	*Geospatial Science and Technology*								
K.2	Geospatial data management, processing and documentation	$151,101	$2,000	$9,850				$25,350	$188,301
K.3	Access to geospatial data holdings	$72,635	$2,000	$2,000				$11,922	$88,557
K.4	Remote monitoring systems and technological engineering	$21,700						$3,376	$25,076
	Total K	**$245,436**	**$4,000**	**$11,850**	**$0**	**$0**	**$0**	**$40,648**	**$301,934**

Project	Project Description	Fiscal Year 2019							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
K	*Geospatial Science and Technology*								
K.2	Geospatial data management, processing and documentation	$113,611	$1,725	$9,850				$32,548	$157,734
K.3	Access to geospatial data holdings	$55,757	$1,725	$450				$15,062	$72,994
K.4	Remote monitoring systems and technological engineering							$0	$0
	Total K	**$169,368**	**$3,450**	**$10,300**	**$0**	**$0**	**$0**	**$47,611**	**$230,728**

Project	Project Description	Fiscal Year 2020							
		Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
K	*Geospatial Science and Technology*								
K.2	Geospatial data management, processing and documentation	$134,521	$2,000	$9,850				$38,056	$184,427
K.3	Access to geospatial data holdings	$66,466	$2,000	$2,000				$18,321	$88,787
K.4	Remote monitoring systems and technological engineering							$0	$0
	Total K	**$200,987**	**$4,000**	**$11,850**	**$0**	**$0**	**$0**	**$56,378**	**$273,214**

Project L. Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP

The remote sensing overflight described in Project L has been postponed and will occur no later than 2021 so that funding can be applied to other priority projects in the FY2018-20 TWP. Specifically funding will be directed towards meeting BiOp Conservation Measures to determine drivers of humpback chub populations within known aggregations and identify additional aggregations and monitor trends of these population segments (see Project elements G.5 and G.6). A portion of the funds for the overflight ($225,000) will be set aside during FY2018-20 and applied to the overflight in the FY2021-23 TWP. We estimate that an additional $275,000 will need to be allocated in year one of the FY2021-23 TWP to implement the overflight, but will look for savings in the current TWP to help offset this cost. By collecting the data in Year 1 of the next work plan, we will be able to produce the derived cartographic (Multispectral Image Mosaic) and analytical (Digital Surface Model) products in Year 2, and develop classified data sets (landcover - e.g., river channel, sand, vegetation) in Year 3.

1. Investigators

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2. Project Summary

This project seeks to collect system-wide, high-resolution multispectral imagery and a Digital Surface Model (DSM) of the Colorado River corridor from the forebay of GCD downstream to Lake Mead, and along the major tributaries to the Colorado River. The proposed schedule for this data collection mission would be in May of 2021, during the first year of the FY2021-23 TWP. The data sets derived from previous remote sensing overflights have proven to be extremely valuable to many of the research projects conducted by GCMRC over the past two decades (Draut and Rubin, 2008; Grams and others, 2010; Ralston and others, 2008; Sankey and others, 2015a; Sankey and others, 2015b). More importantly, scientific research which relied heavily on these data were the basis for the 2016 LTEMP planning and will be used in the ROD implementation process (U.S. Department of Interior, 2016).

The LTEMP states sediment as a resource of key interest and a primary driver for many of the proposed flows defined in the LTEMP ROD. Specifically, the document describes the long-term effects of HFEs and other dam operations on sandbar deposition and rehabilitation, and strategically collected aerial photography and photogrammetrically-derived DSMs provide greater context and understanding of trends otherwise measured through the Sandbar and Sediment Storage Monitoring and Research project (Project B) with remote camera photographs, topographic surveys conducted at the long-term monitoring sandbar sites, and extended, reach-based channel mapping surveys. Derived overflight image-based data sets that classify system-wide areas of exposed sand will assist these field-based methods in quantifying sediment storage throughout the CRe on a decadal time scale. Additionally, adjusted elevation data from the DSM surface will be merged with the topographic and bathymetric data collected during channel mapping surveys (Project B.2) to develop full channel geometry maps for specific segments of the river, allowing for more complete volumetric calculations and improved hydrologic flow modeling of the system over time.

The importance of cultural resources is described in the LTEMP objective and resources. Similar to the sediment storage project, the overflight imagery and derived data sets will play an important role in measuring and tracking changes in sediment and vegetation at cultural resource sites as defined in LTEMP (East and others, 2016). An imagery data set collected during this TWP would provide the next necessary time interval for future inventory and monitoring of these sites.

Riparian vegetation has also been identified as a key resource in the LTEMP. The ability for researchers (Riparian Vegetation Monitoring, Project C) to monitor changes in woody riparian vegetation in response to dam operations is dependent upon the acquisition of new imagery data sets that are consistent with those previously collected (Sankey and others, 2015a,b). Data collection needs to conducted at a time interval that allows researchers to track key vegetation changes such as encroachment onto sandbars, a process known to cause channel narrowing (Dean and Schmidt, 2011) and quantify the reduction in exposed sand area (Sankey and others, 2015a). Lastly, classifications derived from the imagery data will be used to detect vegetation succession at the landscape-scale for woody species and some obligate herbaceous riparian species (Ralston and others, 2008). Strategically planning the appropriate time interval for future missions provides optimization of measurements on the long-term response of riparian vegetation to dam operations under the new LTEMP and the preferred alternative.

Fish monitoring efforts occurring in the Colorado River downstream of GCD, in the LCR downstream of Blue Springs, and in other Colorado River tributaries in Grand Canyon now use the current overflight data (Durning and others, 2016) for spatial positioning of sampling data, navigating waterways and side canyons, and recording contextual site information. Colorado River fish sampling since 2012 has been based on a GIS reference system derived from the two most recent remote sensing imagery data sets (Yard and others, 2016). While a new imagery data set collected in 2021 may not warrant updating the existing mainstem fish sampling system, the new imagery will certainly be used as a critical data reference for the next five to seven years of fish monitoring.

Use of the proposed May 2021 imagery data set is a distinct and important tool that assists many of the proposed projects in this TWP. The overflight is a resource that has both an immediate and a longer-term (e.g., decadal) payoff. For these reasons, this project is mission critical to successfully inform the GCDAMP on performance of the LTEMP ROD.

3. Background

The physical, environment and geographic setting of the Colorado River in Grand Canyon has always provided a constant challenge to monitoring resources of the CRe. Remote sensing provides the means for obtaining valuable information on resources and phenomena that span large geographic areas and found in rugged, often inaccessible environments. There have been numerous remote sensing overflight missions conducted in the CRe in Grand Canyon over many decades (Davis, 2002), with a systematic and concerted effort put forth during GCMRC's tenure as the science provider of the GCDAMP. As the GCDAMP enters its next phase under the new LTEMP, there remains a need to effectively monitor CRe resources synoptically, holistically and at a temporal increment that provides meaningful information to the program as it relates to LTEMP implementation over the next 20 years.

GCMRC's Scientific Monitoring Plan in support of LTEMP, notes that the ROD "calls for a comprehensive, decadal-scale assessment of the impact of dam operations on sandbar resources and on the status of humpback chub" (VanderKooi and others, 2017). Given the physical, geographic and logistical constraints of the study site, it is evident that a need still exists for remotely-sensed data to complement ground-based data collection and assist with the Center's efforts to effectively assess these impacts for the entire system over decadal time frames. While this proposed work is discussed within the context of the next TWP, the nature and justifications for conducting the next overflight is directed at the Center's ability to respond to and deliver information for the LTEMP implementation process that tracks decadal-scale changes to resources system-wide. It is also anticipated that future LTEMP studies will require similar information that can be effectively derived from remotely-sensed data acquired over the next two decades.

GCMRC has historically conducted remote sensing overflight missions to collect high-resolution aerial photography in support of scientific research focused on many of the key resources of concern within the CRe. A remote sensing initiative conducted from 1999 through 2000 determined the most appropriate technologies and methods for acquiring high-resolution imagery to document the status of resources and analyze canyon-wide changes to these resources over time (Davis, 2002; Davis and others, 2002). From this effort is was concluded that acquiring digital imagery every four years for the entire length of the Colorado River between GCD and Lake Mead would be the most appropriate time frame for mapping and performing change detection analysis on these key resources. This led to a series of remote sensing overflight missions conducted in years 2002, 2005, 2009 and 2013 (Davis, 2012, 2013; Durning and others, 2016). Positional accuracies and data integrity of the imagery certainly improved with each subsequent mission during this era. It also became apparent, however, that a quadrennial overflight time frame was resource intensive; in the last TWP we postponed the overflight mission to evaluate our collection window and discover the LTEMP recommendations. After evaluation of the LTEMP ROD we suggest a five- or six-year mission interval would best serve implementation of the ROD.

Listed here are key image products since 2002 and an example of how they have been used:

- *Cartographic products (i.e. River map books):* Used by all projects with field-data collection component that require high-resolution, spatially accurate features.
- *Colorado River Centerline and River Mile System:* The river mile system was updated based on 2009 and 2013 imagery to reflect the drop in Lake Mead and subsequent "new' river channel that emerged between RM 260 and Pearce Ferry (now at RM 281). Lees Ferry is RM zero and count increases in a downstream progression.
- *DSM:* Merged with bathymetric and topographic data to generate a full channel geometry data set used for hydrologic flow modeling, and to determining low-angle slope characteristics of near-shore environments in Glen Canyon (Kaplinski and others, 2014). Used to asses gully annealing and the effects on active sand (Sankey and Draut, 2014).
- *Geomorphic Base Map:* Classification of channel eddy and geomorphic deposits relative to bounding channel features.
- *Modeled Flowlines:* The DSM from the 2002 overflight mission was used to delineate estimated elevations of modeled flows for the Colorado River between Lees Ferry and Diamond Creek (Magirl and others, 2008).
- *Shoreline:* Extract water surface from imagery that serves as an important boundary layer that demarks the water edge of the river at 226.5 m^3/s (8,000 ft^3/s) , this layer was used as the basis for delineating the current fish sampling units used by most monitoring efforts in the mainstem (Durning and others, 2017a, data release)
- *Land cover classification:* Map exposed sand and other geologic/geomorphic features from the imagery for an expanded set of regions of interest.
- *Vegetation classification:* Monitor and track changes in total vegetation, vegetation-sand dynamism and vegetation succession (Ralston and others, 2008; Durning and others, 2017b, data release).

4. Proposed Work

4.1. Project Elements

Project Element L.1. Remote sensing overflight in support of long-term monitoring and LTEMP

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Durning, Research Specialist Sr., Northern Arizona University
Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

It is proposed that GCMRC conducts a system-wide remote sensing overflight to collect digital, multispectral imagery of the CRe between GCD and Lake Mead in May 2021. To maintain consistency with previously collected digital, orthorectified aerial imagery (2002, 2009, 2013), we recommend that this mission be conducted during the same time of year (Memorial Day weekend) and adheres to much of the same data collection parameters and significant logistical requirements as used in preceding missions. For data collection parameters, we require at least the same 4-band wavelength ranges (red, green, blue, and near infra-red), using the same or similar equipment (Leica ADS-80 camera mounted in fixed-wing aircraft), with the option of two cameras and aircraft being made available to increase the rate of data collection, and reduce the impact on dam operations. Wavelengths and other technical details will be specified with the Scope of Work contract and similar to or improved upon those used in previous data collection efforts. The proposed 2021 overflight would be within the LTEMP flow regime, we would request from and work with the Bureau of Reclamation and Western Area Power Administration to maintain a low steady flow of 226 m^3/s (8,000 ft^3/s) for the duration of the data collection period. This flow adjustment is required to maintain consistency in imagery data sets collected in previous years. This will allow for highly accurate image matching and change detection analysis. If a spring HFE occurs in 2021, we will work closely with other GCMRC scientists and the Bureau of Reclamation to ensure all needs are met. We would not expect the presence or absence of a fall HFE in 2019 to affect the proposed May mission. As the LTEMP states, 'triggers for a fall HFE would be met 77% of the years in the LTEMP period', thus we conclude fall HFEs would be a part of the decadal measurement trend.

4.2. Deliverables

As the data collection mission is tentatively scheduled to be conducted in the 3rd Quarter of the first year of the FY2021-23 TWP, most deliverables are not to be expected until at least midway through the second fiscal year of the next work plan. There can be expected, however, an overflight post-mission report that includes specifics on the success of the mission and possibly a tentative timeline for when products will be made available from 1) the entity contracted with to collect the data, and 2) GCMRC staff performing the post-processing of imagery and development of derived data sets.

5. References

Davis, P.A., 2002, Review of remote-sensing and GIS technologies and approaches that may provide alternative ecological monitoring tools for the Grand Canyon Monitoring and Research Center: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, unpublished report, 83 p.

Davis, P.A., 2012, Airborne digital-image data for monitoring the Colorado River corridor below Glen Canyon Dam, Arizona, 2009—Image-mosaic production and comparison with 2002 and 2005 image mosaics: U.S. Geological Survey Open-File Report 2012–1139, 82 p., http://pubs.usgs.gov/of/2012/1139/.

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, 15 p., http://pubs.usgs.gov/ds/780/.

Davis, P.A., Staid, M.I., Plescia, J.B., and Johnson, J.R., 2002, Evaluation of airborne image data for mapping riparian vegetation within the Grand Canyon: U.S. Geological Survey Open-File Report 02-470, 66 p., http://pubs.usgs.gov/of/2002/0470/pdf/of02-470.pdf.

Dean, D.J., and Schmidt, J.C., 2011, The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region: Geomorphology, v. 126, no. 3-4, p. 333-349, http://dx.doi.org/10.1016/j.geomorph.2010.03.009.

Draut, A.E., and Rubin, D.M., 2008, The role of aeolian sediment in the preservation of archaeological sites, Colorado River corridor, Grand Canyon, Arizona, *in* van Riper, C., III, and Sogge, M.K., eds., The Colorado Plateau III—Integrating research and resource management for more effective conservation: Tucson, University of Arizona Press, p. 331-350.

Durning, L.E., Sankey, J.B., Davis, P.A., and Sankey, T.T., 2016, Four-band image mosaic of the Colorado River corridor downstream of Glen Canyon Dam in Arizona, derived from the May 2013 airborne image acquisition: U.S. Geological Survey Data Series 1027, https://doi.org/10.3133/ds1027.

Durning, L.E., Chain, G.R., Sankey, J.B., and Sankey, T.T., 2017a, Colorado River in the Grand Canyon water classification derived from 2013 airborne image collection: U.S. Geological Survey Data Set, https://dx.doi.org/10.5066/F7PZ5799.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, T.T., 2017b, Total vegetation classification within in the Grand Canyon riparian corridor derived from 2013 airborne image collection: U.S. Geological Survey Data Set, https://doi.org/10.5066/F7K64GJF.

East, A.E., Collins, B.D., Sankey, J.B., Corbett, S.C., Fairley, H.C., and Caster, J.J., 2016, Conditions and processes affecting sand resources at archeological sites in the Colorado River corridor below Glen Canyon Dam, Arizona: U.S. Geological Survey Professional Paper 1825, 104 p., http://dx.doi.org/10.3133/pp1825.

Grams, P.E., Hazel, J.E., Schmidt, J.C., Kaplinski, M., Wright, S.A., Topping, D.J., and Melis, T.S., 2010, Geomorphic response of sandbars to the March 2008 high-flow experiment on the Colorado River downstream from Glen Canyon Dam, *in* Hydrology and sedimentation for a changing future—Existing and emerging issues (Joint Federal Interagency Conference 2010—Federal Interagency Hydrologic Modeling, 4th, and Federal Interagency Sedimentation, 9th), Las Vegas, Nev., June 27-July 1, 2010, Proceedings: Proceedings of the Federal Interagency Sedimentation Conferences, U.S. Subcommittee on Sedimentation, p. CD-ROM, http://acwi.gov/sos/pubs/2ndJFIC/Contents/5D_Grams.pdf.

Kaplinski, M.A., Hazel, J.E., Grams, P.E., and 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.

Kasprak, A., Caster, J.J., and Bangen, S.G., 2017, Geomorphic process from topographic form—Automating the interpretation of repeat survey data in river valleys: Earth Surface Processes and Landforms, early view, available at http://dx.doi.org/10.1002/esp.4143.

Magirl, C.S., Breedlove, M.J., Webb, R.H., and Griffiths, P.G., 2008, Modeling water-surface elevations and virtual shorelines for the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Scientific Investigations Report 2008-5075, 32 p., http://pubs.usgs.gov/sir/2008/5075.

Ralston, B.E., Davis, P.A., Weber, R.M., and Rundall, J.M., 2008, A vegetation database for the Colorado River ecosystem from Glen Canyon Dam to the western boundary of Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008-1216, 37 p., http://pubs.usgs.gov/of/2008/1216/.

Sankey, J.B., and 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, v. 220, p. 68-80, http://dx.doi.org/10.1016/j.geomorph.2014.05.028.

Sankey, J.B., East, A.E., Collins, B.D., and Caster, J.J., 2015a, Gully annealing by fluvially-sourced aeolian sand—Remote sensing investigations of connectivity along the fluvial-aeolian-hillslope continuum on the Colorado River, *in* Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nev., April 19-23, 2015: p. 37-43, http://acwi.gov/sos/pubs/3rdJFIC/Proceedings.pdf.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015b, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, http://dx.doi.org/10.1002/2015JG002991.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 196 p., http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Yackulic, C.B., Schmidt, J.C., and Sankey, J.B., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

Yard, M.D., Korman, J., Walters, C.J., and Kennedy, T.A., 2016, Seasonal and spatial patterns of growth of rainbow trout in the Colorado River in Grand Canyon, Arizona: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 125-139, http://dx.doi.org/10.1139/cjfas-2015-0102.

6. Budget

		Fiscal Year 2018							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**

		Fiscal Year 2019							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**

		Fiscal Year 2020							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**

Project M. Administration

The Administration budget covers salaries for the administrative assistant, librarian, budget analyst, the three members of the logistics support staff, as well as leadership and management personnel for GCMRC. Leadership and management personnel salaries include those for the GCMRC Chief and Deputy Chief as well as half the salary for one program manager. Travel and training includes most of the travel and training costs for administrative personnel and the cost of GCMRC staff to travel to AMWG and TWG meetings. Operating expenses includes 1) GSA vehicle costs including monthly lease fees, mileage costs, and any costs for accidents and damage; 2) DOI vehicle costs including gas, maintenance, and replacements costs; 3) GCMRC's Information Technology equipment costs; and 4) a $20,000 annual contribution to the equipment and vehicles working capital fund. Cooperator funding is for support of the Partners in Science Program with Grand Canyon Youth.

Budget

		Fiscal Year 2018							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
M	***Administration***								
M.1	Admin	$618,824	$40,000	$133,000				$123,184	$915,008
M.2	Logistics	$284,226	$5,000			$10,000		$45,295	$344,521
M.3	IT			$100,000				$15,557	$115,557
	Total M	**$903,050**	**$45,000**	**$233,000**	**$0**	**$10,000**	**$0**	**$184,036**	**$1,375,086**

		Fiscal Year 2019							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
M	***Administration***								
M.1	Admin	$622,433	$42,000	$135,500				$207,983	$1,007,916
M.2	Logistics	$258,835	$5,500			$10,500		$69,042	$343,877
M.3	IT			$100,000				$26,000	$126,000
	Total M	**$881,268**	**$47,500**	**$235,500**	**$0**	**$10,500**	**$0**	**$303,025**	**$1,477,793**

		Fiscal Year 2020							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
M	***Administration***								
M.1	Admin	$686,211	$42,000	$136,000				$224,695	$1,088,906
M.2	Logistics	$269,078	$6,000			$11,000		$71,850	$357,928
M.3	IT			$100,000				$26,000	$126,000
	Total M	**$955,289**	**$48,000**	**$236,000**	**$0**	**$11,000**	**$0**	**$322,545**	**$1,572,834**

Disclaimers

Project N. Hydropower Monitoring and Research

1. Investigators

Lucas Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary

The LTEMP ROD (U.S. Department of the Interior, 2016a) states that the objective of the hydropower and energy resource goal is to, "maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources." Project N will identify, coordinate, and collaborate with external partners on monitoring and research opportunities associated with operational experiments at GCD designed to meet hydropower and energy resource objectives, as stated in the LTEMP ROD (U.S. Department of the interior, 2016a).

Operational experiments include proposed experiments in the LTEMP EIS (U.S. Department of Interior, 2016b), and other identified operational scenarios at GCD to improve hydropower and energy resources, while consistent with improvement and long-term sustainability of other downstream resources. Project N will prioritize monitoring and research of proposed experiments in the LTEMP EIS and consider impacts of other proposed experiments on hydropower and energy as part of the experimental design. Project N will also utilize metrics in the LTEMP EIS (U.S. Department of Interior, 2016b) and research by Jenkins-Smith and others (2016) to inform opportunities to incorporate the total economic value of hydropower into the assessment of operational changes at GCD. Coordinated project implementation and development will occur between Reclamation, Western Area Power Administration (WAPA), and other collaborators to utilize and build on existing hydropower and energy models and data, specifically from Appendix K in the LTEMP EIS (U.S. Department of Interior, 2016b).

3. Hypotheses and Science Questions

Specific hypotheses and science questions to be addressed will be determined in coordination with Reclamation, WAPA, and other collaborators during Project N implementation and development.

4. Background

Project N would meet critical socioeconomic information needs identified by the GCDAMP (AMWG, 2012). Furthermore, the implementation of proposed experiments in the LTEMP EIS are, "contingent on the responses of one or more socioeconomic metrics" (VanderKooi and others, 2017). The role of the GCMRC, and its cooperators, is to provide information on physical and biological resources while also providing information related to socioeconomic aspects of resources, including hydropower (VanderKooi and others, 2017). Project N will focus on monitoring and research opportunities, utilizing past and ongoing research at GCMRC, Reclamation, and WAPA, to provide information related to the hydropower and energy objectives identified in the LTEMP ROD (U.S. Department of the Interior, 2016a).

5. Proposed Work

5.1. Project Elements

Project Element N.1. Hydropower monitoring and research

Lucas Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Project N will identify, coordinate, and collaborate on monitoring and research opportunities associated with operational experiments at GCD to meet hydropower and energy resource objectives, as stated in the LTEMP ROD (U.S. Department of the Interior, 2016a). Operational experiments include experiments proposed in the LTEMP EIS (e.g., HFEs, macroinvertebrate production flows, trout management flows) or experiments that improve hydropower and energy resources (e.g., change in ramp rates, change in daily flow range, fluctuating flow factors, monthly volume patterns), while consistent with improvement and long-term sustainability of other downstream resources. Monitoring and research of hydropower and energy resources will be prioritized, in consultation and coordination with Reclamation, WAPA, and other collaborators, based on the sequence of proposed experiments in the LTMEP EIS (U.S. Department of Interior, 2016b), availability of predictive models to assess downstream resource conditions in response to experiments designed to improve hydropower and energy resources, and/or the magnitude of economic impacts of operational changes at GCD.

Project N will estimate and attempt to minimize impacts of proposed experiments in the LTEMP EIS (U.S. Department of Interior 2016b) on hydropower as part of the experimental design. To minimize impacts to hydropower and energy resources, Project N will consider and measure the total value of hydropower generated at GCD. To categorize the total value for hydropower, Project N will utilize the impacts defined in the LTEMP EIS (U.S. Department of Interior, 2016b) and research by Jenkins-Smith and others (2016). The impacts associated with changes in hydropower generation because of proposed experiments in the LTEMP EIS, or future experimental operational scenarios, include, but are not limited to, greenhouse gas emissions, regional visibility, human health, and regional impacts to farmers, ranchers, and associated rural communities, including tribal communities.

Coordination will occur between GCMRC, Reclamation, WAPA, and other collaborators in the implementation of Project N, including the utilization and development of existing hydropower and regional power system models and data, specifically modeling and data from the LTEMP

EIS (U.S. Department of Interior, 2016b). Project N will be dependent on monitoring and research collaboration with technical staff from Reclamation, WAPA, and other collaborators and subject-matter experts in the development of models, design of experiments and monitoring of hydropower and energy metrics.

5.2. Deliverables

Products from this project will be determined in coordination with Reclamation, WAPA, and other collaborators during Project N implementation and development. When applicable, presentations will be given at TWG and AMWG meetings, presentations at scientific meetings, and peer-reviewed scientific journal articles.

6. References

Glen Canyon Dam Adaptive Management Work Group (AMWG), 2012, Recommended information needs and program elements for a proposed AMP socioeconomics program as approved by AMWG on February 23, 2012: Phoenix, Ariz., AMWG, https://www.usbr.gov/uc/rm/amp/amwg/mtgs/12feb22/Attach_07b.pdf.

Jenkins-Smith, H.C., Silva, C.L., Carlson, D., Gupta, K., Jones, B., Ripberger, J., Wehde, W., and Berrens, R., 2016, Estimating non-use values for alternative operations of the Glen Canyon Dam—An inclusive value approach—Phase 3B project reseach and findings: Norman, OK, University of Oklahoma and Sandia National Laboratories, Center for Energy, Security and Society, 89 p., http://cess.ou.edu/resources/2016093-GCD_3B_FinalReport.pdf.

U.S. Department of Interior, 2016a, Record of decision for the Glen Canyon Dam long-term experimental and management plan final environmental impact statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

U.S. Department of Interior, 2016b, Glen Canyon Dam Long-term Experimental and Management Plan final Environmental Impact Statement (LTEMP FEIS): U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 8 chapters plus 17 appendices, http://ltempeis.anl.gov/documents/final-eis/.

VanderKooi, S.P., Kennedy, T.A., Topping, D.J., Grams, P.E., Ward, D.L., Fairley, H.C., Bair, L.S., Sankey, J.B., Yackulic, C.B., and Schmidt, J.C., 2017, Scientific monitoring plan in support of the selected alternative of the Glen Canyon Dam Long-Term Experimental and Management Plan: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, U.S. Geological Survey Open-File Report 2017-1006, 18 p., https://doi.org/10.3133/ofr20171006.

7. Budget

Project	Project Description	Fiscal Year 2018 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,296	$750	$300				$1,610	$11,956
	Total N	**$9,296**	**$750**	**$300**	**$0**	**$0**	**$0**	**$1,610**	**$11,956**

Project	Project Description	Fiscal Year 2019 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,575	$750	$375				$2,782	$13,482
	Total N	**$9,575**	**$750**	**$375**	**$0**	**$0**	**$0**	**$2,782**	**$13,482**

Project	Project Description	Fiscal Year 2020 Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,863	$750	$375				$2,857	$13,845
	Total N	**$9,863**	**$750**	**$375**	**$0**	**$0**	**$0**	**$2,857**	**$13,845**

Appendix 1. Lake Powell Water Quality Monitoring

In the text below we provide context and background for a subset of the work that is being conducted under the Interagency Agreement R13PG40028 between the Bureau of Reclamation and GCMRC (funded through mid-year FY2019). The work aims to better constrain the important drivers of nutrient outflow from GCD and to capitalize and expand upon a large volume of historical nutrient data that has been collected in Lake Powell and within the draft intake tubes of GCD. We describe the work's relevance to the GCDAMP and some of the guiding hypotheses behind this work in the sections that follow. We then provide an updated scope of work description that is in the process of being incorporated into a modification to the Interagency Agreement.

1. Background

A number of physical and biogeochemical processes in Lake Powell affect the nutrient concentration of dam releases; however, we lack a good quantitative understanding of the relative importance of these different reservoir processes in determining variation in nutrient concentrations in Lake Powell's outflow. More generally, the high uncertainty concerning drivers of water quality in Lake Powell's outflow was highlighted in the recent knowledge assessment conducted by the TWG of the GCDAMP, in which this category consistently had the highest uncertainty (Braun, 2017). This lack of understanding impedes our ability to predict how various actions discussed in the LTEMP BiOp (e.g., retrofitting the dam to draw waters from different reservoir depths) will affect the CRe, or to predict how effects from environmental factors (e.g., prolonged drought) on GCDAMP priority resources such as rainbow trout and humpback chub may override impacts from experimental flows associated with the LTEMP. Furthermore, the August 2016 fisheries PEP recommended additional study of reservoir dynamics as a priority emerging issue, with specific emphasis on a better understanding of temperature and nutrients including the potential impacts of releases from the meta- and epilimnetic regions of the reservoir and increasing influence of quagga mussel (*Dreissena bugensis*) on nutrient and temperature conditions.

Historical data from the Lake Powell water quality monitoring program have already been used for a number of important purposes including the development of a CE-QUAL-W2 model and the description of long term trends in stratification and associated oxygen dynamics (Williams, 2007). Still, there has been relatively little effort to describe nutrient dynamics within the reservoir aside from some early work demonstrating the important role of advection in the system (Gloss and others, 1980) and some recent work to show the composition of various phosphorus fractions in inlet deltaic sediments (Wildman and Hering, 2011). Historical data suggests Lake Powell is functioning as a net phosphorous sink given higher concentrations of phosphorous in the reservoir inflows than in the outflow (Vernieu, 2009). In particular, Lake

Powell outflows often have very low concentrations of SRP, the form of phosphorous that is used most readily by the primary producers that form the basis of foodwebs in both Lake Powell and the CRe. While concentrations of SRP are always relatively low (mean of 5 µg L^{-1} in the water exiting GCD), they have also varied substantially through time (factor of three variation in SRP concentration within a single season between 2012 and 2016 alone, Vernieu, 2009).

Nutrients have been monitored at penstock depth 2.4 kilometers upstream of Lake Powell since the early 1990s; however the detection limit for key nutrients (e.g., SRP) was relatively high until 2001, and thus temporal patterns in the 1990s are partially obscured. Following changes in detection, the degree of temporal variation in nutrients like SRP became much clearer. In a broad sense, SRP has been relatively high during two periods (the late 1990s and 2008-2014), and currently appears to be trending towards the extremely low concentrations more typical of the early to mid-2000s (Project E, Figure 1). Past efforts to understand and predict water quality in the outflow from Lake Powell has focused on other attributes (e.g., predicting water temperature with a two dimensional hydrodynamic and water quality model, CE-QUAL-W2, Williams, 2007), with much less focus on understanding temporal patterns in nutrients like SRP. Given recent findings that SRP may be a key driver of ecosystem productivity in the CRe, there is a need to more closely examine historical data including data from elsewhere in Lake Powell and estimates of SRP loading that can be derived from historical measurements along the Green, Colorado and San Juan Rivers. Analyses of these data should help us test some very broad hypotheses concerning drivers of temporal variation of SRP in Lake Powell.

2. Hypotheses

The Colorado and San Juan Rivers deliver large amounts of total phosphorous to Lake Powell; however, much of this phosphorous is bound to fine sediments and is deposited in the deltaic sediments. As the elevation of Lake Powell drops, these deltaic sediments can become repeatedly exposed and re-inundated. It has been hypothesized (H1) that inundation of these sediments may lead to surges of SRP flowing out of the deltas into Lake Powell (Wildman and Hering, 2011). In many systems, P release during re-inundation is driven by shifting redox conditions, wherein iron (Fe) bound P is released as sediments go anoxic (Boström and others, 1988; Kinsman-Costello and others, 2014). In Lake Powell, this mechanism is not likely to be very important since Fe bound P makes up only a very small fraction of the total P in deltaic sediments (Wildman and Hering, 2011). Instead, the mineralization of organic P under dry conditions (when sediments are more aerobic) may produce a sizeable, loosely bound, and easily exchangeable SRP pool that can be mobilized into the water column upon re-inundation. In fact, previous characterization of sediment P fractions in Lake Powell's sediment delta show that a sizeable fraction of P is bound to organic material (Wildman and Hering, 2011). P mobilized from deltaic sediments is most likely to be transported towards the dam in winter and early spring when there is less biological uptake of SRP within the reservoir and inflow waters tend to flow under the Lake Powell epilimnion. This hypothesis suggests that the interaction of season, low lake elevation, and high inflows should lead to increased SRP in metalimnion and hypolimnion waters, leading to increased SRP discharge at GCD. However, an alternative hypothesis (H2) is that high inflow nutrient loading itself may bring high concentrations of SRP into Lake Powell (i.e., that low lake elevation may not be necessary for surges of SRP). Distinguishing between these hypotheses is important for predicting how climate, water policy (e.g., the 2007 Interim Guidelines), or both may affect overall phosphorous cycles in Lake Powell.

Water densities in Lake Powell vary both over time and with depth. Waters with different densities sink to different depths within the lake, resulting in density stratification. Lake inflows also vary in density over time. The interaction between the density of inflows and existing density stratification in Lake Powell determines the depth to which inflows sink as they enter the Lake Powell water column. Water temperature and salinity are the primary factors determining water density, and both the density of the inflowing water and the density stratification within the reservoir change through time. We hypothesize (H3) that SRP rich waters which end up closer to the surface are less likely to contribute to increased SRP in the outflow, both because the SRP is more likely to be taken up by primary producers in the light-saturated surface waters (epilimnion) of the Lake Powell ecosystem and because primary producers will elevate pH in these upper waters, leading to increased rates of co-precipitation of SRP with calcium carbonate. Given the long residence time of water in Lake Powell (2-3 years) and its horizontal and vertical mixing dynamics, we also hypothesize (H4) that SRP concentrations in Lake Powell outflow may reflect inflow conditions over many years and not just the single prior year. Lastly, we hypothesize that an important factor affecting SRP concentrations in the lake and its outflow over the last few years, and in the future, may be the continued establishment of quagga mussels (*Dreissena bugensis*) in the lake. The mussels may decrease dissolved nutrients by filtering phytoplankton and zooplankton from the water column (Hecky and others, 2004), and may even alter thermal stratification regime via their capacity to dramatically increase water clarity. This specific hypothesis, and the more general need to integrate our understanding of Lake Powell nutrient dynamics with our understanding of the CRe were identified as a priority by the 2016 fisheries PEP.

While we expect that SRP concentrations in Lake Powell outflows have historically been primarily driven by the magnitude and seasonal timing of inflows, the amount of exposed deltaic sediments, and the interactions of inflows with existing reservoir stratification (i.e., H1-H4), outflow SRP concentrations may increasingly be affected by quagga mussels (H5). We also hypothesize that dam operations and potential infrastructure changes can alter SRP concentrations in Lake Powell outflows. In particular, we hypothesize (H6) that drawing water through the jet tubes (either during HFEs or if retrofitting of jet tubes is pursued after the feasibility study dictated by the LTEMP EIS and associated BiOp) could elevate riverine SRP concentrations in dam outflows. This effect would arise because of the higher concentrations of phosphorus found in the reservoir's bottom waters (Vernieu, 2009). In addition, past work suggests some support for hypothesis H7, that dam operations such as high flow events, can lead to substantially mixing of stratified layers within Lake Powell. For example, Hueftle and Stevens (2001) showed that the 1996 spring HFE diminished hypoxia in the hypolimnion as far as 100 km up-lake from GCD while also resulting in high salinity, high dissolved oxygen concentrations, and damped fluctuations in dissolved oxygen and pH in the dam tailwater (Hueftle and Stevens, 2001). Nutrient data collected four days before and two days after the 1996 spring HFE showed drops in phosphorus concentration at both the penstock and river outlet works (Hueftle and Stevens, 2001), although the magnitude of this drop is difficult to determine given the detection limit of the analyses used at that time. Monitoring during the 2008 HFE also showed elevated dissolved oxygen concentrations immediately downstream of the dam (at maximum 120% of saturation), but relatively minimal effects on the structure of the water column up-lake of the dam (Vernieu, 2010). Still, the Vernieu 2010 study only considered water temperature, specific conductance, and dissolved oxygen, but not nutrients. Lastly, the amount of water stored in Lake Powell is also clearly a factor in determining temperature and nutrients in the outflow so long as the depth from which the penstocks draw water is fixed. There tends to be more phosphorus in the colder hypolimnion (bottom waters) than in the warmer epilimnion (surface waters), but the relationship between water level and outflow phosphorus concentrations is not straightforward in the historical dataset suggesting the importance of other drivers like inflow, quagga mussels, and sediment deltaic dynamics.

3. Scope of Work

The objectives of this monitoring program have changed since 1965, reflecting changes in scientific interest as the reservoir filled, responsibilities of Reclamation for maintaining salinity levels in the Colorado River, and the monitoring status of upper Colorado River Basin reservoirs. Objectives have also been responsive to more recent environmental concerns related to the Grand Canyon Protection Act, the establishment of the GCDAMP, and the GCD LTEMP EIS and subsequent ROD.

Objectives of this long-term monitoring program include:

1) Determination of water-quality status and trends in Lake Powell and GCD releases
2) Linking the historical record of Lake Powell water quality to various climatological and hydrological conditions
3) Documentation of the effects of the structure and operation of GCD on the quality of water in Lake Powell and GCD releases
4) Integration with GCDAMP information needs and downstream monitoring programs
5) Documentation of the density structure and associated nutrient distribution in the water column at the GCD forebay and other locations in the reservoir to determine the quality of water available for release from GCD

6) Assessment of the distribution and patterns of major ionic constituents in Lake Powell and GCD releases
7) Assessment of the distribution and patterns of nutrient constituents in Lake Powell and GCD releases
8) Assessment of the structure, status, and trends of the plankton community and its effect on primary and secondary production in Lake Powell.

Element H.1. Details of ongoing monitoring program (to be continued under this agreement)

The ongoing Lake Powell water-quality monitoring program consists of monthly surveys of the reservoir forebay and tailwater (conducted by GCMRC) and quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms of the reservoir to the inflow areas (conducted by Reclamation). The GCD forebay station is located approximately 2.4 km upstream from GCD. Two tailwater sites are located immediately downstream from the dam and at Lees Ferry, approximately 25 km downstream. Depending on reservoir elevation, 25-30 established sites, including the forebay and tailwater stations, are sampled for the quarterly surveys.

At each site, initial surface observations (for example, bottom depth, Secchi depth, weather observations) are recorded, after which a depth profile of temperature, specific conductance, dissolved oxygen, pH, redox potential, turbidity, and chlorophyll florescence is collected, using the Seabird SBE19plusV2 instrument. These data are downloaded immediately after collection and viewed in the field to determine stratification patterns. Based on stratification patterns, chemical samples for major ionic constituents and nutrient concentrations are collected in the major strata at selected sites. Dissolved organic carbon samples are collected at the forebay, tailwater, and tributary inflow sites. Biological samples for chlorophyll concentration, phytoplankton, and zooplankton are also collected at selected sites. Samples are filtered and preserved in the field for subsequent laboratory analysis.

Analysis for major ionic constituent, nutrient, and chlorophyll concentrations are performed by Reclamation's Lower Colorado Regional Laboratory in Boulder City, NV. Phytoplankton and zooplankton samples are analyzed under contract by BSA Environmental, Inc. Data processing of the Seabird profile data is performed in the office shortly after the field survey. All field and analytical data are entered into the GCMRC water quality database (WQDB) database for statistical and graphical analysis and long-term storage.

Details of the monitoring program, a description of the WQDB database, and physicochemical data from 1965-2013 are available as a USGS Data Series report at https://pubs.usgs.gov/ds/471/.

Element H.2. Historical data analysis—Towards improved predictive capacity for reservoir nutrient dynamics

Given the large volume of historical nutrient data available for Lake Powell, the river outlet works, and Lees Ferry, and given that there has been relatively little analysis of the nutrient data, GCMRC will spend time assessing spatial and temporal trends in nutrient concentrations and potential environmental drivers of nutrient availability. The historical data from this monitoring program has already been used for a number of important purposes including the development of a working CE-QUAL2 model and the description of long term trends in stratification and associated oxygen dynamics. Still, there is a great deal of additional analysis that can be done to better elucidate the controls on reservoir and outlet chemistry. Work by Wildman and Hering suggests that deltaic sediments in the inlets of Lake Powell may be a dominant source of phosphorus to the reservoir (via re-mobilization during flooding event; Wildman and Hering, 2011). Still, there is also substantial variation in inflow concentrations of nutrients that may also control in-reservoir availability. Finally, recent work done in other systems (streams and lakes) has shown the important role that calcium carbonate formation can play in sequestering phosphorus from the water column.

To understand the fate of nutrient loading to Lake Powell's inlets, the USGS program LOADEST will be used in combination with historic discharge and nutrient concentrations (records generally exist from 1990-2000) from the USGS National Water Information System (NWIS) stations: Green River at Green River, Colorado River near Cisco Utah, and San Juan River at Bluff. Modeled riverine nutrient loading for this decade will be compared to nutrient measurements in the Lake Powell dataset to look for an advective signal of riverine nutrient loading. If nutrient loading from inlets does not appear to be driving nutrient dynamics at the dam, we will explore the role of deltaic sediment nutrient loading via coring experiments. We will also use the long term dataset to look for evidence of phosphorus sequestration via calcium carbonate deposition (using chlorophyll a, pH, [Ca^{2+}], conductivity, alkalinity, turbidity, and secchi depth data) and changes in water column chemistry post-quagga mussel establishment. Together, these data sources will help us better identify the most important processes controlling P availability in Lake Powell and GCD releases and will also inform the development of future sampling and experimental plans. Ultimately, our goal is to be able to model SRP concentrations at the GCD outflow.

Element H.3. Revisions to existing program

Given recent evidence that the nutrient content of Lake Powell's outflow is an important driver of biological processes in downstream ecosystems (Yackulic, 2017), the ongoing monitoring at the Wahweap station will be expanded to better capture nutrient dynamics along a vertical profile. The necessary degree of increased resolution will be determined based on preliminary sampling at very high resolution (15+ depths) during thermally stratified conditions when nutrient content is expected to vary the most by depth. Currently, nutrient samples are collected at the Wahweap station monthly from the surface, bottom, and from the depth of the penstock. Based on the initial highly resolved sampling, depths will be chosen that adequately represent transitions between density layers while avoiding re-sampling within regions of homogenous nutrient concentration. Depths will be matched with the forebay thermistor string maintained by Reclamation such that temperature can be used as a tracer of vertical mixing. To best support this approach, we will also deploy a string of conductivity sensors near the thermistor string to better characterize density mixing. Nutrient samples will also be collected from within the interflow at each inlet site during the quarterly sampling (Escalante, San Juan, and Colorado). The interflow will be identified by looking at the Seabird conductivity, turbidity, and temperature profiles and this sampling will help us determine to what extent excess P may be getting mobilized off of sediment deltas during higher inflow events. Depending on the results of this sampling and the historical data analysis, additional targeted sampling may be conducted in the reservoir inlets to better ascertain the controls on nutrient transformation and transport.

In addition to expanded sampling at Wahweap and inlet sites, historical data will be thoroughly assessed to look for redundancies in sample effort. For example, a thorough comparison of measurements being made at Wahweap, within the draft tubes, and at Lees Ferry will be conducted in order to assess the necessity of maintaining each of these sites. Methodology for chlorophyll sample collection will also be examined systematically so as to properly assess differences between methods and annotate the WQDB accordingly. Samples were previously preserved via desiccation, but are now chilled or frozen.

Element H.4. Characterizing nutrient dynamics during experimental flows

The potential for experimental flows to modify downstream nutrient regimes will be examined by conducting targeted nutrient sampling before, during, and after experimental flows. Previous sampling efforts have documented the capacity for changes in flow at GCD outlets to affect the chemistry of water below the dam. For example, work by Hueftle and Stevens showed that the 1996 spring high flow event diminished bottom water hypoxia in Lake Powell as far as 100 km uplake while also resulting in high salinity, high oxygen concentrations, and damped DO and pH fluctuations in the dam tailwater (Hueftle and Stevens, 2001). Nutrient data collected 4 days before and 2 days after the high flow event showed drops in phosphorus concentration at both the penstock and river outlet works, although the magnitude of this drop is difficult to determine given the detection limit of the analyses used at that time. Monitoring during the 2008 HFE also showed elevated dissolved oxygen concentrations downstream of the dam (at maximum 120% of saturation), but relatively minimal effects on the structure of the water column upstream of the dam (Vernieu, 2010). Still, this study only considered water temperature, specific conductance, and dissolved oxygen, not nutrients. Targeted profiling at Wahweap and grab sampling at Lees Ferry will be conducted at least twice prior to experimental flow, twice during experimental flow, and twice post experimental flow to better quantify the effects of flow regime on reservoir and outlet chemistry. Thermistor string data will also be examined for changes in physical stratification as well as nutrient dynamics.

Element H.5. Improving access to historical dataset

Given the relatively unique and valuable nature of the historic Lake Powell water quality database, GCMRC will identify an appropriate, easily visible online location for the dataset to facilitate public access and download. GCMRC currently maintains the Lake Powell water quality database in-house in a Microsoft Access™ format. A static download of data through 2013 is available in association with Data Series Report DS-471; however a currently-updated version of the database is not available for download on the GCMRC website. After quality control-checking the current WQDB, the data will be made available online in a central location to be determined by the requesting agency, the servicing agency, and interested stakeholders and cooperators. Options include: a link to the Access database on the GCMRC website that is periodically updated, importing the data to NWIS, or adding the data to a new Water Quality Portal that serves to aggregate data from across government agencies (e.g. the U.S. Environmental Protection Agency, the USGS, and the National Water Quality Monitoring Council) resulting in a current 297 million water quality records from more than 2.7 million distinct sites (https://www.waterqualitydata.us/).

4. References

Boström, B., Andersen, J.M., Fleischer, S., and Jansson, M., 1988, Exchange of phosphorus across the sediment-water interface: Hydrobiologia, v. 170, no. 1, p. 229-244, http://dx.doi.org/10.1007/BF00024907.

Braun, D.P., 2017, GCDAMP FY 2017 Knowledge Assessment—Final report from the executive coordinator for the Science Advisors Program: Glen Canyon Dam Adaptive Management Program (GCDAMP), Science Advisors Program, Technical Work Group (TWG): 31 p., http://gcdamp.com/index.php?title=2017_Knowledge_Assessment.

Gloss, S.P., Mayer, L.M., and Kidd, D.E., 1980, Advective control of nutrient dynamics in the epilimnion of a large reservoir: The American Society of Limnology and Oceanography, v. 25, no. 2, p. 219-28, http://dx.doi.org/10.4319/lo.1980.25.2.0219.

Hecky, R.E., Smith, R.E.H., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N., and Howell, T., 2004, The nearshore phosphorus shunt—A consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes: Canadian Journal of Fisheries and Aquatic Sciences, v. 61, no. 7, p. 1285-1293, https://doi.org/10.1139/f04-065.

Hueftle, S.J., and Stevens, L.E., 2001, Experimental flood effects on the limnology of Lake Powell reservoir, southwestern USA: Ecological Applications, v. 11, no. 3, p. 644-656, http://www.jstor.org/stable/pdfplus/3061107.pdf.

Kinsman-Costello, L.E., O'Brien, J.M., and Hamilton, S.K., 2014, Re-flooding a historically drained wetland leads to rapid sediment phosphorus release: Ecosystems, v. 17, no. 4, p. 641-656, http://dx.doi.org/10.1007/s10021-014-9748-6.

Vernieu, W.S., 2009, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964-2013: U.S. Geological Survey Data Series 471, 23 p., http://dx.doi.org/10.3133/ds471.

Vernieu, W.S., 2010, Effects of the 2008 high-flow experiment on water quality in Lake Powell and Glen Canyon Dam releases, Utah-Arizona: U.S. Geological Survey Open-File Report 2010-1159, 25 p., http://pubs.usgs.gov/of/2010/1159/.

Wildman, R.A., Jr., and Hering, J.G., 2011, Potential for release of sediment phosphorus to Lake Powell (Utah and Arizona) due to sediment resuspension during low water level: Lake and Reservoir Management, v. 27, no. 4, p. 365-375, http://dx.doi.org/10.1080/07438141.2011.632705.

Williams, N.T., 2007, Modeling dissolved oxygen in Lake Powell using CE-QUAL-W2: Provo, Utah, Brigham Young University, M.S. in Science, Department of Civil and Environmental Engineering, 120 p., https://deercreek.groups.et.byu.net/Papers/Models/W2-MODEL/DO_ModelingPowell_WilliamsThesis.pdf.

Yackulic, C.B., 2017, The role of nutrients in Colorado River ecosystem dynamics—Annual reporting meeting presentation for FY16—January 26-27, 2017: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Bureau of Reclamation, Glen Canyon Adaptive Management Program, https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR20_Yackulic.pdf.

5. Budget

		Fiscal Year 2018							
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
	Lake Powell								
	Lake Powell	$80,775	$39,322	$6,868				$20,314	$147,279

		Fiscal Year 2019							
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
	Lake Powell								
	Lake Powell (1/2 year only)	$38,332	$10,988	$6,969				$14,635	$70,924

		Fiscal Year 2020							
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
	Lake Powell								
	Lake Powell							$0	$0

Appendix 2a. Potential Budget Allocation Summary by Project and Year

		FY18-20 Summary		
Project	Project Description	FY18	FY19	FY20
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***	$1,229,646	$1,251,097	$1,317,861
B	***Sandbar and Sediment Storage Monitoring and Research***	$1,039,115	$1,110,925	$1,043,962
C	***Riparian Vegetation Monitoring and Research***	$584,657	$485,251	$456,692
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***	$261,903	$293,737	$297,905
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***	$342,754	$232,715	$256,724
F	***Aquatic Invertebrate Ecology***	$771,248	$811,143	$779,902
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***	$1,506,095	$1,674,368	$1,681,653
H	***Salmonid Research and Monitoring***	$683,065	$725,679	$698,640
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***	$557,090	$581,299	$577,347
J	***Socioeconomic Research in the Colorado River Ecosystem***	$281,305	$252,145	$257,956
K	***Geospatial Science and Technology***	$301,934	$230,728	$273,214
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***	$75,000	$75,000	$75,000
M	***Administration***	$1,375,086	$1,477,793	$1,572,834
N	***Hydropower Monitoring & Research***	$11,956	$13,482	$13,845
	GCMRC AMP Total	**$9,020,855**	**$9,215,361**	**$9,303,535**
	Anticipated GCMRC AMP Funds (80%)	**$8,820,363**	**$8,908,567**	**$8,997,653**
	Over/Under Budget	**($200,492)**	**($306,794)**	**($305,882)**
	Native Fish Conservation Contingency Fund	$43,000	$294,000	$145,000
	Anticipated Carryover (From Previous FY)	$332,000	$174,508	$161,713
	GCMRC AMP Total Over/Under Budget (w/Fish Funds & Carryover)	**$174,508**	**$161,713**	**$832**
	Lake Powell	$150,000	$70,924	$0
	GCMRC Grand Total (w/ Lake Powell)	**$9,170,855**	**$9,286,285**	**$9,303,535**

Appendix 2b. Potential Budget Allocation – FY2018

		Fiscal Year 2018							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
							Burden Rate	15.557%	
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$146,500	$2,000	$5,000	$29,000		$183,609	$28,392	$394,501
A.2	Water quality	$82,200	$2,000	$20,000	$29,000		$54,200	$20,722	$208,122
A.3	Sediment transport and budgeting	$302,900	$6,000	$55,000	$29,000		$173,000	$61,123	$627,023
	Total A	**$531,600**	**$10,000**	**$80,000**	**$87,000**	**$0**	**$410,809**	**$110,237**	**$1,229,646**
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$173,274	$2,000	$4,500	$29,896	$200,308		$38,628	$448,606
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$201,283	$2,000	$15,000		$192,308		$39,728	$450,320
B.3	Control network and survey support	$63,755	$1,900	$15,000	$40,662			$18,873	$140,190
	Total B	**$438,312**	**$5,900**	**$34,500**	**$70,558**	**$392,616**	**$0**	**$97,228**	**$1,039,115**
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$114,608	$1,821	$3,000	$65,000	$8,500		$28,947	$221,877
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$118,502	$1,821	$1,000		$79,000		$21,244	$221,568
C.3	Vegetation responses to LTEMP flow scenarios		$1,821			$90,710		$3,005	$95,536
C.4	Vegetation management decision support	$37,706	$1,821					$6,149	$45,676
	Total C	**$270,817**	**$7,285**	**$4,000**	**$65,000**	**$178,210**	**$0**	**$59,345**	**$584,657**
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$152,693	$4,750	$11,075	$21,958			$29,632	$220,108
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$33,668	$2,500					$5,627	$41,795
	Total D	**$186,361**	**$7,250**	**$11,075**	**$21,958**	**$0**	**$0**	**$35,259**	**$261,903**
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$107,796	$2,000	$34,469	$4,400			$23,128	$171,793
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$67,231	$5,000	$63,302	$3,500	$10,000		$21,929	$170,962
	Total E	**$175,026**	**$7,000**	**$97,771**	**$7,900**	**$10,000**	**$0**	**$45,057**	**$342,754**

		Fiscal Year 2018							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
F	*Aquatic Invertebrate Ecology*								
F.1	Influence of dam operations on the food base	$294,337	$6,650	$26,000	$20,000	$8,000		$54,221	$409,208
F.2	Aquatic food base status at humpback chub monitoring locations	$97,174						$15,117	$112,291
F.3	Terrestrial-aquatic linkages	$19,571		$1,700		$26,250		$4,097	$51,618
F.4	Glen Canyon aquatic food base monitoring and research	$80,067	$12,500	$4,000				$15,023	$111,590
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$71,390	$2,500	$1,000				$11,651	$86,541
	Total F	**$562,539**	**$21,650**	**$32,700**	**$20,000**	**$34,250**	**$0**	**$100,108**	**$771,248**
G	*Humpback Chub Population Dynamics throughout the Colorado River Ecosystem*								
G.1	Humpback chub population modeling	$78,290	$2,000	$3,000				$12,957	$96,247
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$7,201		$8,500	$88,080	$337,506		$26,270	$467,557
G.3	Juvenile chub monitoring near the LCR confluence	$138,763		$17,000	$139,500			$45,934	$341,197
G.4	Remote PIT tag array monitoring in the LCR	$37,395		$3,500	$6,000			$7,295	$54,190
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$22,258		$8,000	$42,616	$84,240		$13,864	$170,978
G.6	Juvenile chub monitoring – West	$85,857		$12,000	$114,500			$33,036	$245,393
G.7	Chute Falls translocations	$6,890		$3,000	$8,000	$65,520		$4,749	$88,159
G.8	Havasupai translocation feasibility							$0	$0
G.9	Backwater Seining	$20,669		$5,000	$11,000			$5,705	$42,374
	Total G	**$397,323**	**$2,000**	**$60,000**	**$409,696**	**$487,266**	**$0**	**$149,811**	**$1,506,095**
H	*Salmonid Research and Monitoring*								
H.1	Experimental flow assessment of trout recruitment	$188,594		$25,160	$101,492	$60,000		$50,843	$426,089
H.2	Rainbow and brown trout recruitment and outmigration model	$73,693						$11,464	$85,157
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$41,266		$300		$18,285		$7,015	$66,866
H.4	Rainbow trout monitoring in Glen Canyon				$15,952	$84,000		$5,002	$104,954
	Total H	**$303,552**	**$0**	**$25,460**	**$117,444**	**$162,285**	**$0**	**$74,324**	**$683,065**
I	*Warm-Water Native and Non-Native Fish Research and Monitoring*								
I.1	System-wide native fish and invasive aquatic species monitoring	$58,115	$500	$2,000	$71,255	$210,000		$26,815	$368,685
I.2	Improve early detection of warm-water invasive fish	$9,769			$9,732	$21,000		$3,664	$44,165
I.3	Assess the risks warm-water nonnative fish pose to native fish	$103,821	$1,000	$20,000				$19,418	$144,239
	Total I	**$171,706**	**$1,500**	**$22,000**	**$80,987**	**$231,000**	**$0**	**$49,897**	**$557,090**
J	*Socioeconomic Research in the Colorado River Ecosystem*								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$55,778	$2,500	$600		$71,500		$11,305	$141,683
J.2	Applied decision and scenario analysis	$87,687	$750	$300		$36,000		$14,885	$139,622
	Total J	**$143,465**	**$3,250**	**$900**	**$0**	**$107,500**	**$0**	**$26,189**	**$281,305**

		Fiscal Year 2018							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
K	*Geospatial Science and Technology*								
K.2	Geospatial data management, processing and documentation	$151,101	$2,000	$9,850				$25,350	$188,301
K.3	Access to geospatial data holdings	$72,635	$2,000	$2,000				$11,922	$88,557
K.4	Remote monitoring systems and technological engineering	$21,700						$3,376	$25,076
	Total K	**$245,436**	**$4,000**	**$11,850**	**$0**	**$0**	**$0**	**$40,648**	**$301,934**
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**
M	***Administration***								
M.1	Administration	$618,824	$40,000	$133,000				$123,184	$915,008
M.2	Logistics	$284,226	$5,000			$10,000		$45,295	$344,521
M.3	IT			$100,000				$15,557	$115,557
	Total M	**$903,050**	**$45,000**	**$233,000**	**$0**	**$10,000**	**$0**	**$184,036**	**$1,375,086**
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,296	$750	$300				$1,610	$11,956
	Total N	**$9,296**	**$750**	**$300**	**$0**	**$0**	**$0**	**$1,610**	**$11,956**
	GCMRC AMP Total	**$4,338,484**	**$115,585**	**$613,556**	**$880,543**	**$1,613,128**	**$485,809**	**$973,749**	**$9,020,855**
	Anticipated GCMRC AMP Funds (80%)								**$8,820,363**
	AMP Over/Under Budget								**($200,492)**
	Native Fish Conservation Contingency Fund								$43,000
	Anticipated Carryover (From Previous FY)								$332,000
	GCMRC AMP Total Over/Under Budget (w/Fish Funds & Carryover)								**$174,508**
	Lake Powell								
	Lake Powell	$80,775	$39,322	$6,868				$19,752	$146,717
	GCMRC Grand Total (w/ Lake Powell)	**$4,419,259**	**$154,907**	**$620,424**	**$880,543**	**$1,613,128**	**$485,809**	**$993,501**	**$9,167,572**

Appendix 2c. Potential Budget Allocation – FY2019

		Fiscal Year 2019							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
							Burden Rate	26.000%	
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$150,900	$2,000	$5,100	$29,600		$186,600	$48,776	$422,976
A.2	Water quality	$84,700	$2,000	$10,200	$29,600		$55,300	$32,890	$214,690
A.3	Sediment transport and budgeting	$255,050	$6,100	$56,100	$29,600		$176,400	$90,181	$613,431
	Total A	**$490,650**	**$10,100**	**$71,400**	**$88,800**	**$0**	**$418,300**	**$171,847**	**$1,251,097**
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$178,472	$2,000	$4,500	$32,388	$188,960		$62,182	$468,502
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$186,222	$2,000	$7,500	$91,006	$180,960		$79,978	$547,666
B.3	Control network and survey support	$58,304	$1,900	$15,000				$19,553	$94,757
	Total B	**$422,998**	**$5,900**	**$27,000**	**$123,394**	**$369,920**	**$0**	**$161,713**	**$1,110,925**
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$88,203	$685	$2,700	$61,000	$8,500		$39,928	$201,016
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$65,109	$685			$82,000		$19,566	$167,360
C.3	Vegetation responses to LTEMP flow scenarios		$685			$87,948		$2,817	$91,450
C.4	Vegetation management decision support	$19,493	$685					$5,246	$25,424
	Total C	**$172,806**	**$2,740**	**$2,700**	**$61,000**	**$178,448**	**$0**	**$67,557**	**$485,251**
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$157,669	$4,750	$11,850	$24,044			$51,561	$249,874
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$34,811						$9,051	$43,862
	Total D	**$192,481**	**$4,750**	**$11,850**	**$24,044**	**$0**	**$0**	**$60,612**	**$293,737**
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$34,026	$2,000	$28,774	$2,400			$17,472	$84,672
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$78,694	$6,000	$21,126	$3,500	$10,000		$28,723	$148,043
	Total E	**$112,720**	**$8,000**	**$49,900**	**$5,900**	**$10,000**	**$0**	**$46,195**	**$232,715**

		Fiscal Year 2019							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
F	***Aquatic Invertebrate Ecology***								
F.1	Influence of dam operations on the food base	$295,291	$6,850	$26,000	$20,600			$90,673	$439,414
F.2	Aquatic food base status at humpback chub monitoring locations	$92,995						$24,179	$117,174
F.3	Terrestrial-aquatic linkages	$20,158		$1,751		$27,038		$6,507	$55,454
F.4	Glen Canyon aquatic food base monitoring and research	$82,469	$12,875	$4,120				$25,861	$125,325
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$56,152	$2,400					$15,224	$73,776
	Total F	**$547,065**	**$22,125**	**$31,871**	**$20,600**	**$27,038**	**$0**	**$162,443**	**$811,143**
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***								
G.1	Humpback chub population modeling	$75,161	$2,000	$3,000				$20,842	$101,003
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$8,194		$8,500	$91,200	$337,506		$38,178	$483,578
G.3	Juvenile chub monitoring near the LCR confluence	$139,356		$17,000	$150,000			$79,653	$386,009
G.4	Remote PIT tag array monitoring in the LCR	$38,517		$6,000	$6,000			$13,134	$63,651
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$32,817		$10,500	$88,468	$84,240		$36,791	$252,816
G.6	Juvenile chub monitoring – West	$61,459		$12,000	$125,000			$51,599	$250,058
G.7	Chute Falls translocations	$9,582		$3,000	$8,000	$65,520		$7,317	$93,419
G.8	Havasupai translocation feasibility							$0	$0
G.9	Backwater Seining	$21,289		$2,000	$11,500			$9,045	$43,834
	Total G	**$386,374**	**$2,000**	**$62,000**	**$480,168**	**$487,266**	**$0**	**$256,559**	**$1,674,368**
H	***Salmonid Research and Monitoring***								
H.1	Experimental flow assessment of trout recruitment	$195,119	$7,420	$22,410	$111,092	$60,000		$89,171	$485,212
H.2	Rainbow and brown trout recruitment and outmigration model	$41,715						$10,846	$52,561
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$26,558		$600		$43,616		$8,370	$79,144
H.4	Rainbow trout monitoring in Glen Canyon				$17,652	$84,000		$7,110	$108,762
	Total H	**$263,392**	**$7,420**	**$23,010**	**$128,744**	**$187,616**	**$0**	**$115,496**	**$725,679**
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***								
I.1	System-wide native fish and invasive aquatic species monitoring	$38,449	$500		$80,665	$210,000		$37,400	$367,014
I.2	Improve early detection of warm-water invasive fish	$10,062	$1,000	$200	$10,872	$27,500		$6,580	$56,214
I.3	Assess the risks warm-water nonnative fish pose to native fish	$102,452	$1,000	$22,000				$32,618	$158,070
	Total I	**$150,964**	**$2,500**	**$22,200**	**$91,537**	**$237,500**	**$0**	**$76,597**	**$581,299**
J	***Socioeconomic Research in the Colorado River Ecosystem***								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$86,177	$2,500	$750		$71,500		$25,396	$186,323
J.2	Applied decision and scenario analysis	$51,115	$750	$375				$13,582	$65,822
	Total J	**$137,292**	**$3,250**	**$1,125**	**$0**	**$71,500**	**$0**	**$38,979**	**$252,145**

		Fiscal Year 2019							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
K	***Geospatial Science and Technology***								
K.2	Geospatial data management, processing and documentation	$113,611	$1,725	$9,850				$32,548	$157,734
K.3	Access to geospatial data holdings	$55,757	$1,725	$450				$15,062	$72,994
K.4	Remote monitoring systems and technological engineering							$0	$0
	Total K	**$169,368**	**$3,450**	**$10,300**	**$0**	**$0**	**$0**	**$47,611**	**$230,728**
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**
M	***Administration***								
M.1	Administration	$622,433	$42,000	$135,500				$207,983	$1,007,916
M.2	Logistics	$258,835	$5,500			$10,500		$69,042	$343,877
M.3	IT			$100,000				$26,000	$126,000
	Total M	**$881,268**	**$47,500**	**$235,500**	**$0**	**$10,500**	**$0**	**$303,025**	**$1,477,793**
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,575	$750	$375				$2,782	$13,482
	Total N	**$9,575**	**$750**	**$375**	**$0**	**$0**	**$0**	**$2,782**	**$13,482**
	GCMRC AMP Total	**$3,936,953**	**$120,485**	**$549,231**	**$1,024,187**	**$1,579,788**	**$493,300**	**$1,511,416**	**$9,215,361**
	Anticipated GCMRC AMP Funds (80%)								**$8,908,567**
	AMP Over/Under Budget								**($306,794)**
	Native Fish Conservation Contingency Fund								$294,000
	Anticipated Carryover (From Previous FY)								$174,508
	GCMRC AMP Total Over/Under Budget (w/Fish Funds & Carryover)								**$161,713**
	Lake Powell								
	Lake Powell (1/2 year only)	$38,332	$10,988	$6,969				$14,635	$70,924
	GCMRC Grand Total (w/ Lake Powell)	**$3,975,285**	**$131,473**	**$556,200**	**$1,024,187**	**$1,579,788**	**$493,300**	**$1,526,051**	**$9,286,285**

Appendix 2d. Potential Budget Allocation – FY2020

		Fiscal Year 2020							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
							Burden Rate	26.000%	
A	***Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem***								
A.1	Stream gaging	$155,400	$2,100	$5,200	$30,200		$190,300	$50,154	$433,354
A.2	Water quality	$87,300	$2,100	$10,200	$30,200		$56,400	$33,748	$219,948
A.3	Sediment transport and budgeting	$291,050	$6,200	$57,200	$30,200		$179,900	$100,009	$664,559
	Total A	**$533,750**	**$10,400**	**$72,600**	**$90,600**	**$0**	**$426,600**	**$183,911**	**$1,317,861**
B	***Sandbar and Sediment Storage Monitoring and Research***								
B.1	Sandbar monitoring using topographic surveys and remote cameras	$183,826	$2,000	$4,500	$32,388	$200,308		$63,915	$486,938
B.2	Bathymetric and topographic mapping for monitoring long-term trends in sediment storage	$213,542	$2,000	$7,500		$173,817		$63,205	$460,064
B.3	Control network and survey support	$60,053	$1,900	$15,000				$20,008	$96,961
	Total B	**$457,421**	**$5,900**	**$27,000**	**$32,388**	**$374,126**	**$0**	**$147,128**	**$1,043,962**
C	***Riparian Vegetation Monitoring and Research***								
C.1	Ground-based riparian vegetation monitoring	$105,013	$425	$1,500	$40,000	$8,500		$38,459	$193,897
C.2	Imagery-based riparian vegetation monitoring at the landscape scale	$66,725	$425	$1,000		$84,000		$20,239	$172,389
C.3	Vegetation responses to LTEMP flow scenarios					$87,773		$2,633	$90,406
C.4	Vegetation management decision support							$0	$0
	Total C	**$171,738**	**$850**	**$2,500**	**$40,000**	**$180,273**	**$0**	**$61,331**	**$456,692**
D	***Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites***								
D.1	Geomorphic effects of dam operations and vegetation management	$163,616	$4,750	$7,100	$24,974			$52,114	$252,554
D.2	Cultural resources synthesis to inform Historic Preservation Plan	$35,993						$9,358	$45,351
	Total D	**$199,609**	**$4,750**	**$7,100**	**$24,974**	**$0**	**$0**	**$61,472**	**$297,905**
E	***Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future***								
E.1	Temperature and nutrients in the CRe – patterns, drivers, and improved predictions	$35,047	$2,000	$19,627	$2,400			$15,359	$74,433
E.2	Linking temperature and nutrients to metabolism and higher trophic levels	$112,131	$4,000	$16,870	$3,500	$10,000		$35,790	$182,291
	Total E	**$147,178**	**$6,000**	**$36,497**	**$5,900**	**$10,000**	**$0**	**$51,149**	**$256,724**

		Fiscal Year 2020							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
F	***Aquatic Invertebrate Ecology***								
F.1	Influence of dam operations on the food base	$302,261	$7,055	$26,000	$21,218			$92,699	$449,233
F.2	Aquatic food base status at humpback chub monitoring locations	$97,353						$25,312	$122,665
F.3	Terrestrial-aquatic linkages							$0	$0
F.4	Glen Canyon aquatic food base monitoring and research	$88,958	$13,261	$4,244				$27,680	$134,143
F.5	Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?	$58,620						$15,241	$73,861
	Total F	**$547,192**	**$20,316**	**$30,244**	**$21,218**	**$0**	**$0**	**$160,932**	**$779,902**
G	***Humpback Chub Population Dynamics throughout the Colorado River Ecosystem***								
G.1	Humpback chub population modeling	$83,058	$2,000	$3,000				$22,895	$110,953
G.2	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the LCR	$13,818		$8,500	$93,800	$337,506		$40,316	$493,941
G.3	Juvenile chub monitoring near the LCR confluence	$143,537		$17,000	$153,000			$81,520	$395,057
G.4	Remote PIT tag array monitoring in the LCR	$39,672		$6,000	$6,000			$13,435	$65,107
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$28,619		$10,500	$47,948	$84,240		$25,165	$196,472
G.6	Juvenile chub monitoring – West	$63,303		$12,000	$128,000			$52,859	$256,162
G.7	Chute Falls translocations	$9,870		$3,000	$8,000	$65,520		$7,392	$93,782
G.8	Havasupai translocation feasibility				$8,000	$14,400		$2,512	$24,912
G.9	Backwater Seining	$21,928		$2,000	$12,000			$9,341	$45,269
	Total G	**$403,804**	**$2,000**	**$62,000**	**$456,748**	**$501,666**	**$0**	**$255,433**	**$1,681,653**
H	***Salmonid Research and Monitoring***								
H.1	Experimental flow assessment of trout recruitment	$187,143	$7,236	$25,160	$113,864	$60,000		$88,485	$481,888
H.2	Rainbow and brown trout recruitment and outmigration model	$5,642						$1,467	$7,109
H.3	Using early life history and physiological growth data from otoliths to inform management of rainbow trout and brown trout populations in Glen Canyon	$79,255						$20,606	$99,861
H.4	Rainbow trout monitoring in Glen Canyon				$18,462	$84,000		$7,320	$109,782
	Total H	**$272,040**	**$7,236**	**$25,160**	**$132,326**	**$144,000**	**$0**	**$117,878**	**$698,640**
I	***Warm-Water Native and Non-Native Fish Research and Monitoring***								
I.1	System-wide native fish and invasive aquatic species monitoring	$39,602	$500		$83,160	$210,000		$38,348	$371,610
I.2	Improve early detection of warm-water invasive fish	$10,364	$1,000		$11,472	$21,000		$6,567	$50,403
I.3	Assess the risks warm-water nonnative fish pose to native fish	$100,281	$1,000	$22,000				$32,053	$155,334
	Total I	**$150,247**	**$2,500**	**$22,000**	**$94,632**	**$231,000**	**$0**	**$76,969**	**$577,347**
J	***Socioeconomic Research in the Colorado River Ecosystem***								
J.1	Tribal perspectives for and values of resources downstream of Glen Canyon Dam: Tribal member population survey	$88,763	$2,500	$750		$71,500		$26,068	$189,581
J.2	Applied decision and scenario analysis	$53,142	$750	$375				$14,109	$68,376
	Total J	**$141,904**	**$3,250**	**$1,125**	**$0**	**$71,500**	**$0**	**$40,178**	**$257,956**

		Fiscal Year 2020							
Project	**Project Description**	**Salary & Benefits**	**Travel & Training**	**Operating Expenses**	**Logistics**	**Cooperators (non-USGS)**	**USGS Cooperators**	**USGS Burden**	**Total**
K	***Geospatial Science and Technology***								
K.2	Geospatial data management, processing and documentation	$134,521	$2,000	$9,850				$38,056	$184,427
K.3	Access to geospatial data holdings	$66,466	$2,000	$2,000				$18,321	$88,787
K.4	Remote monitoring systems and technological engineering							$0	$0
	Total K	**$200,987**	**$4,000**	**$11,850**	**$0**	**$0**	**$0**	**$56,378**	**$273,214**
L	***Remote Sensing Overflight in Support of Long-term Monitoring and LTEMP***								
L.1	Remote sensing overflight in support of long-term monitoring and LTEMP						$75,000	$0	$75,000
	Total L	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**
M	***Administration***								
M.1	Administration	$686,211	$42,000	$136,000				$224,695	$1,088,906
M.2	Logistics	$269,078	$6,000			$11,000		$71,850	$357,928
M.3	IT			$100,000				$26,000	$126,000
	Total M	**$955,289**	**$48,000**	**$236,000**	**$0**	**$11,000**	**$0**	**$322,545**	**$1,572,834**
N	***Hydropower Monitoring and Research***								
N.1	Hydropower monitoring and research	$9,863	$750	$375				$2,857	$13,845
	Total N	**$9,863**	**$750**	**$375**	**$0**	**$0**	**$0**	**$2,857**	**$13,845**
	GCMRC AMP Total	**$4,191,021**	**$115,952**	**$534,451**	**$898,786**	**$1,523,565**	**$501,600**	**$1,538,161**	**$9,303,535**
	Anticipated GCMRC AMP Funds (80%)								**$8,997,653**
	AMP Over/Under Budget								**($305,882)**
	Native Fish Conservation Contingency Fund								$145,000
	Anticipated Carryover (From Previous FY)								$161,713
	GCMRC AMP Total Over/Under Budget (w/Fish Funds & Carryover)								**$832**
	Lake Powell								
	Lake Powell							$0	$0
	GCMRC Grand Total (w/ Lake Powell)	**$4,191,021**	**$115,952**	**$534,451**	**$898,786**	**$1,523,565**	**$501,600**	**$1,538,161**	**$9,303,535**

Appendix 2e. Potential Budget Allocation Experimental Projects

		Experimental Fund Budget (Based upon FY19 Costs)							
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	USGS Cooperators	USGS Burden	Total
	Experimental Fund Budget						Burden Rate	26.000%	
A	***LTEMP Flow Experimental Projects***								
A.1	LTEMP Flow Experimental Projects							$0	$20,000
	Total H	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$20,000**
B	***HFE Experimental Projects***								
B.1	Extended duration HFE (no bathymetry)	$6,663	$1,200	$1,000	$71,881	$86,261	$0	$23,581	$190,586
B.2	Proactive HFE (no bathymetry)	$3,284	$1,200	$1,000	$32,503	$61,348	$0	$11,717	$111,052
B.3	Proactive HFE (with bathymetry)	$6,663	$1,200	$1,000	$55,870	$86,261	$0	$19,418	$170,412
B.4	Laboratory Experiments	$19,884	$5,000	$15,000	$0	$63,085	$0	$12,262	$115,231
H	***TMFF Experimental Projects***								
H.1	TELLS	$13,427	$13,000	$7,000	$22,000			$14,411	$69,838
	Total H	**$13,427**	**$13,000**	**$7,000**	**$22,000**	**$0**	**$0**	**$14,411**	**$69,838**