Grand Canyon Monitoring and Research Center Triennial Budget and Work Plan Prospectus—Fiscal Years 2015–2017

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Introduction

FY15/16/17
US Geological Survey Grand Canyon Monitoring and Research Center
Work Plan Prospectus

This document is a summary of likely and potential projects proposed to be conducted in fiscal years 2015 (FY15), 2016 (FY16), and 2017 (FY17) by the US Geological Survey Grand Canyon Monitoring and Research Center (GCMRC). This document also includes a budget summary table that lists the estimated cost of the project and the status of the project as "recommended for funding," 'funding possible," "funding unlikely," and "likely to be funded from other BoR sources."

The purpose of this document is to initiate discussion with stakeholders and sister agencies about the monitoring and research priorities that will guide work activities during the next three years. This document identifies likely and potential projects to be funded in FY15. The primary funding source for these activities will be the Glen Canyon Dam Adaptive Management Program (GCDAMP).

Approximately $8.8 million in GCDAMP funding is anticipated to be available to support GCMRC activities in FY15. The total cost of all potential projects presently identified by GCMRC for consideration as FY15 work activities is approximately $10.8 million. GCMRC anticipates approximately $0.5 million in supplemental funding from the Bureau of Reclamation to support monitoring of Lake Powell reservoir limnology and to continue research activities associated with the landscape-scale geomorphic context of archaeological resources.

At this time, it is essential to identify monitoring and research priorities, because the funds necessary to support all monitoring and research activities greatly exceed the available GCDAMP funds. In an effort to focus attention on the need to assign monitoring and research priorities, this document provides general project descriptions and specific descriptions of work activities.

In early June, GCMRC will release a full draft proposed Work Plan, and each project description will include scientific and administrative background, relation to GCDAMP planning guidance, descriptions of past project performance, and detailed project budgets. The full draft of the proposed Work Plan will also include an extended discussion about how the work plan is responsive to the guidance and suggestions provided by the Budget Ad Hoc Group of the GCDAMP Technical Work Group, guidance and suggestions provided by sister agencies, and relation to the LTEMP EIS process. At that time, a projected work plan and budget for each of the next three years will be released.

GCMRC continues its efforts to identify strategies for reducing the costs of specific projects. We hope that such reductions will result in additional monitoring and research projects being proposed for funding in the new Work Plan. GCMRC staff has worked closely with sister agency staff to identify areas of overlap and redundancy, especially as regards the monitoring of fish populations. GCMRC is grateful for the hard work of the fish science community in this regard.

Nevertheless, it will not be possible to fund all potential projects, and GCMRC seeks input regarding which projects are of most interest to stakeholders. We look forward to informative conversations with sister agencies, the GCDAMP stakeholders, and others interested in the work of the GCMRC.

Potential Budget Allocation

(M)Monitoring (R)Research	Project Identifier			FY15 Potential Budget	recommend for funding	fund if possible	funding potential uncertain	likely to be funded from other BoR sources
		Running Total		**$10,782,000**	**$8,814,000**	**$462,500**	**$997,500**	**$508,000**
M	1	*Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring*	*Vernieu*	*$290,000*				$290,000
M/R	2	Stream Flow, Water Quality, and Sediment Transport in the Colorado River Ecosystem	Topping et al.	$1,413,000	$1,413,000			
	3	Sandbars and Sediment Storage Dynamics						
M	3.1.1	Monitoring sandbars using topographic surveys and remote cameras	Grams et al.	$380,000	$380,000			
M	3.1.2	Monitoring sand bars and shorelines above 8000 ft^3/s by remote sensing	Sankey et al.	$121,000	$121,000			
R	3.1.3	Surveying with a camera: rapid topographic surveys with digital images using structure-from-motion (SFM) photogrammetry	Wheaton et al.	$77,000	$38,500		$38,500	
R/M	3.1.4	Analysis of historical images at selected monitoring sites	Hazel et al.	$178,000	$89,000		$89,000	
R	3.2	Sediment storage monitoring	Grams et al.	$463,000	$463,000			
R	3.3	Characterizing, and predictive modeling, of sand bar response at local and reach scales	Mueller et al.	$101,000	$101,000			
R	3.4	Connecting bed material transport, bed morphodynamics, and sand budgets in Grand Canyon	McElroy et al.	$123,000			$123,000	
M	3.3	Control network and survey support	Kohl	$135,000	$135,000			
	4	Connectivity along the Fluvial-Aeolian-Hillslope Continuum: Quantifying the Relative Importance of River-Related Factors that Influence Upland Geomorphology and Archaeological Site Stability						
R	4.1	*Quantifying connectivity along the fluvial-aeolian-hillslope continuum at landscape scales*	Sankey et al.	$218,000				$218,000
M	4.2	Monitoring of cultural sites in Grand and Glen Canyons	Sankey et al.	$377,000	$188,500	$188,500		
	5	Food Base Monitoring and Research						
R	5.1	Are aquatic insect diversity and production recruitment limited?	Kennedy et al.	$337,000	$300,000	$37,000		
R		*(monitoring and research beyond the CRe)*		*$84,000*			$84,000	
	5.2	Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters						
M	5.2.1	Continue characterizing and monitoring drift and insect emergence in Glen Canyon	Muehlbauer	$52,000	$52,000			
M	5.2.2	Continue natal origins drift monitoring in Glen, Marble, and Grand Canyons	Kennedy	$87,000	$87,000			
R	5.2.3	Link drift at natal origins Project transects to channel bed shear stress	Muehlbauer and Wright	$21,000	$21,000			
R	5.2.4	Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyons	Muehlbauer and Wright	$21,000	$21,000			
R	*5.2.6*	*Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters*	Kennedy et al.	*$141,000*			$141,000	
M	5.3	Primary Production Monitoring in Glen Marble and Grand Canyons	Kennedy et al.	**$41,000**	$41,000			

(M)Monitoring (R)Research	Project Identifier			FY15 Potential Budget	recommend for funding	fund if possible	funding potential uncertain	likely to be funded from other BoR sources
	6	Mainstem Colorado River Humpback Chub Aggregations and Fish Commuity Dynamics						
M	6.1	Mainstem Colorado River Humpback Chub aggregation monitoring	Persons et al.	$232,000	$232,000			
R	6.2	Aggregation recruitment	Dodrill et al.	$87,000	$87,000			
R	6.3	Monitoring mainstem aggregations with PIT tag antennas (pilot)	Ward	$19,000		$19,000		
M	6.4	System Wide Electrofishing	Persons and Rogowski	$302,000	$302,000			
R	6.5	Brown trout natal origins through body pigmentation patterns in the Colorado River	Rowgoski	$16,000			$16,000	
R	6.6	Direct Mainstem Augmentation of Humpback Chub (FY 17?)	Young et al.					
M	6.7	Rainbow Trout Early Life Stage Survey	Avery and Foster	$70,000	$70,000			
M	6.8	Lees Ferry Creel Survey (FY 16 and 17)	Rogowski and Persons	$0		$0		
	7	Population Ecology of Humpback Chub in and around the Little Colorado River						
M	7.1	Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River	Persons et al.	$558,000	$558,000			
M	7.2	Juvenile chub monitoring in the mainstem near the Little Colorado River confluence	Yard et al.	$562,000	$562,000			
R	7.3	July Little Colorado River juvenile humpback chub marking to estimate production and outmigration	Dzul et al.	$119,000	$119,000			
M	7.4	Remote PIT tag array monitoring in the LCR	Persons	$54,000	$54,000			
R	7.5	Food web monitoring in the Little Colorado River	Muehlbauer et al.	$142,000	$142,000			
R	7.6	Potential for gravel substrate limitation for humpback chub reproduction in the LCR	Dzul et al.	$12,000		$12,000		
R	7.7	Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River	Ward and Stone	$86,000	$86,000			
M	7.8	Evaluate effects of Asian tapeworm infestation on Juvenile humpback chub	Ward	$17,000	$17,000			
R	7.9	Development of a non-lethal tool to assess the physiological condition of humpback chub in the Colorado and Little Colorado Rivers	Dibble et al.	$42,000		$42,000		
R	7.10	Humpback chub population modelling	Yackulic and Dzul	$92,000	$92,000			
	8	Management Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon						
R	8.1	Efficacy and ecological impacts of BNT removal	Ward and Healy	$110,000	$110,000			
M	8.2	Translocation and monitoring above Chute Falls	Persons et al.	$89,000	$89,000			
	8.3	Fisheries Protocol Evaluation Panel (FY16 or FY17)	VanderKooi et al.	$0				
M	8.4	Invasive Species Surveillance and Response (FY17)	Young et al.	$0		$0		
R	8.5	Genetic Monitoring of Lower Basin Humpback Chub (FY17)	Wilson et al.	$0			$0	

(M)Monitoring (R)Research	Project Identifier			FY15 Potential Budget	recommend for funding	fund if possible	funding potential uncertain	likely to be funded from other BoR sources
	9	Understanding the Factors Limiting the Growth of Rainbow Trout in Glen and Marble Canyons						
R/M	9.1	Lees Ferry RBT; monitoring, analysis, and study design	Persons et al.	$37,000	$37,000			
R	9.2	Detection of RBT movement from upper Colorado River below GCD (NO)	Yard, Korman, Persons and Rogowski	$484,000	$484,000			
R	9.3	Exploring the mechanisms behind trout growth, reproduction, and movement in Glen and Marble Canyons using lipid (fat) reserves as an indicator of physiological condition	Dibble et al.	$52,000	$52,000			
R	9.4	Comparative study on the feeding morphology of drift feeding fish	Yard et al.	$86,000	$43,000	$43,000		
R	9.5	Meta-analysis and the development of reactive distance relationships for encounter rate models	Yard et al.	$52,000			$52,000	
R	9.6	Lab studies to evaluate turbidity as a potential Glen Canyon Dam-operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub	Ward	$37,000	$37,000			
R	9.7	Application of a bioenergetics model in a seasonally turbid river	Dodrill et al.	$67,000		$67,000		
R	9.8	Mechanisms that limit RBT and BNT growth in other western tailwater systems	Dibble et al.	$72,000	$72,000			
R	9.9	Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management	Yard et al.	$59,000	$59,000			
R	9.10	Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon	Dibble et al.	$54,000		$54,000		
R	10	Mapping and Assessment of Aquatic Habitats below Glen Canyon Dam	Melis et al.	$145,000			$145,000	

	11	Riparian Vegetation Studies: Ground-based and Landscape-scale Riparian Vegetation Monitoring and Plant Response-Guild Research associated with Sandbar Evolution and Wildlife Habitat Analysis						
M	11.1	Ground-based vegetation monitoring	Ralston et al.	$158,000	$158,000			
M	11.2	Periodic landscape scale vegetation mapping and analysis using remotely sensed data	Sankey et al.	$150,000	$150,000			
R	11.3	Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991	Sarr et al.	$130,000			$130,000	
R	11.4	Linking dam operations to changes in terrestrial fauna	Yackulic et al.	$144,000			$144,000	
R	12	Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem	Fairley et al.	$35,000			$35,000	

(M)Monitoring (R)Research	Project Identifier			FY15 Potential Budget	recommend for funding	fund if possible	funding potential uncertain	likely to be funded from other BoR sources
	13	Socio-economic Monitoring and Research						
M/R	13.1	Economic Values of Recreational Resources Along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values	Bair et al.	$70,000	$70,000			
R	13.2	Tribal Values and Perspectives of Resources Downstream of Glen Canyon Dam (FY 16 and 17)	Bair et al.			$0		
R	13.3	Applied Decision Methods for the Glen Canyon Adaptive Management Plan	Bair et al.	$124,000	$124,000			
	14	Administration and Support						
		GIS/database/engineering support	Gushue et al.	$208,000	$208,000			
		GCMRC personnel costs		$550,000	$550,000			
		GCMRC travel-training		$30,000	$30,000			
		GCMRC operations/supply/equipment		$227,000	$227,000			
		working capital		$20,000	$20,000			
		GCMRC logistical support		$274,000	$274,000			
		cooperative/interagency agreements		$70,000	$70,000			
		burden on admin costs		$178,000	$178,000			
		Independent Review						
		Fisheries Protocol Evaluation Panel (see Project 8.3)						

Project 1. Lake Powell and Glen Canyon Dam Release Water-Quality Monitoring

A. Investigators

William S. Vernieu, Hydrologist, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

This project conducts water-quality monitoring on Lake Powell and the Glen Canyon Dam tailwaters. The water-quality monitoring program consists of monthly surveys of the reservoir forebay and tailwater, as well as quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms. Water temperature, specific conductance, dissolved oxygen, pH, redox potential, turbidity, and chlorophyll concentration are measured throughout the water column at up to 30 sites (fig. 1) on the reservoir, with samples for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton being collected at selected sites. The project also includes continuous monitoring of Glen Canyon Dam releases for water temperature, specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll concentration and monthly sampling for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton below the dam and at Lees Ferry.

The data collected by the project describe the current water quality of Glen Canyon Dam releases to the downstream ecosystem, as well as describe the current water-quality conditions and hydrologic processes in Lake Powell, which can be used to predict the quality of future releases from the dam.

It is proposed that the existing water-quality monitoring program will continue through the FY2015-17 period at its current level. The Seabird CTD instrument will continue to be used as the primary profiling device for reservoir stations. Minor changes may be made to the existing program in terms of number of stations sampled and the amount and type of samples collected. Recent data collected from the monitoring program will continue to be published and an interpretive synthesis of existing data will be developed for publication during the FY2015-17 period.

Physical and chemical information from this program was published as Data Series Report DS-471 (Vernieu, 2013). An updated revision to this report is currently in development. Biological data is contained in a separate data series report, currently in review. All information from this program is currently stored in the Microsoft Access water-quality database (WQDB).

It is also proposed that a system for online data access and dissemination will be developed during this time. This will involve migration of the current WQDB database into an Oracle database to enhance online data availability. A web site will also be developed that will allow access to currently available data and the interactive display of various graphic products depicting summarized data collected by the program. Some aspects of data management and the development of visualization tools will be made in collaboration with the Wisconsin Science Center and Center for Integrated Data Analytics.

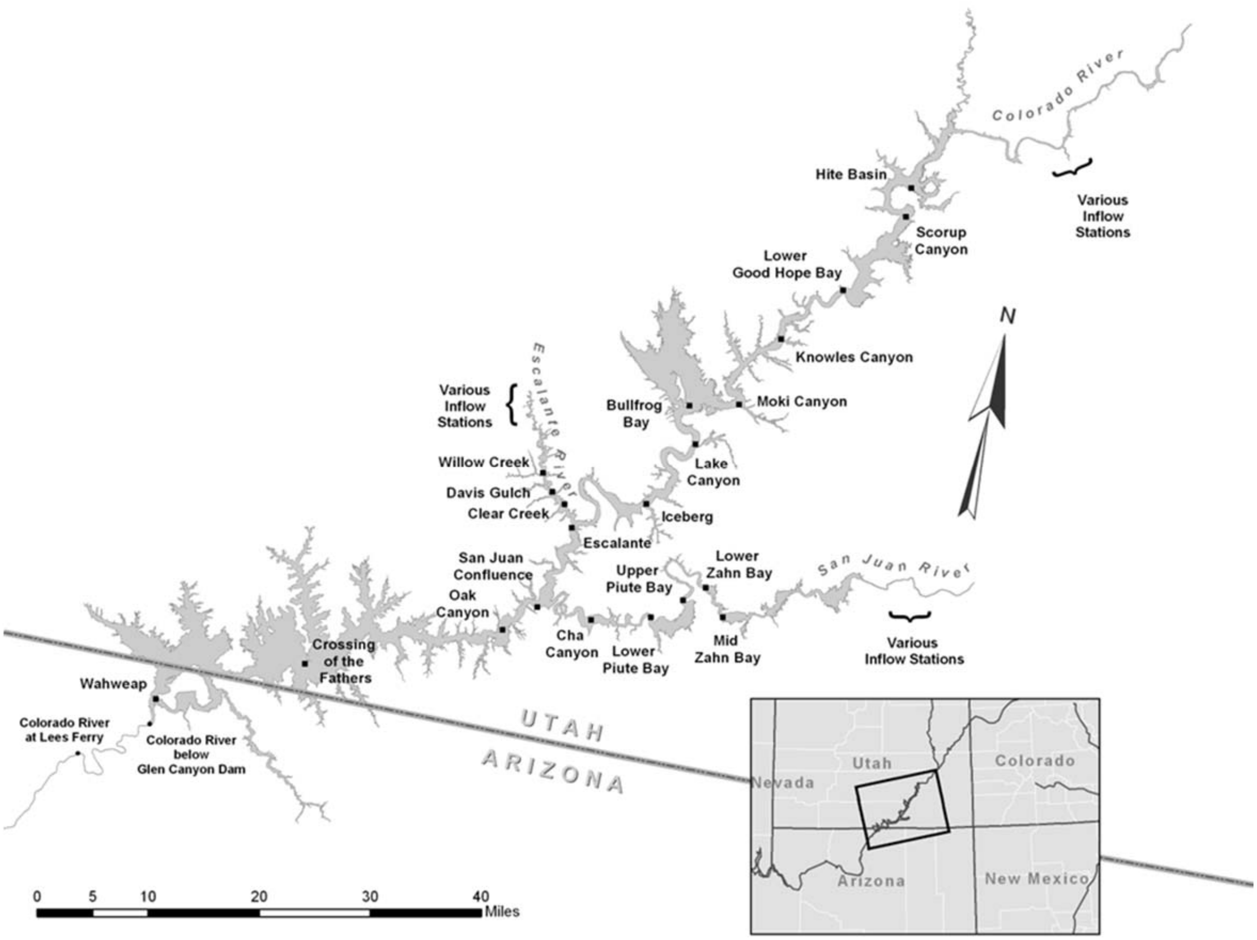

Figure 1. Lake Powell water-quality monitoring locations.

The USGS Grand Canyon Monitoring and Research Center (GCMRC) will work collaboratively with the Bureau of Reclamation (Reclamation) in efforts to enhance simulation modeling of Lake Powell Reservoir water quality and limnology. Modeling will utilize the CE-QUAL-W2 model, a 2D water quality and hydrodynamic model, currently maintained by Reclamation. This model is used to project Glen Canyon Dam release temperatures, and will be enhanced to answer various research questions relating to the fate of inflow currents, effects of reservoir drawdowns, and dissolved oxygen dynamics in the reservoir.

C. Proposed Work

C.1. Project Elements

Monitoring

It is proposed the Lake Powell monitoring program continue in its present structure, consisting of monthly surveys of the reservoir forebay and tailwater, as well as quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms. Depth profiles of water temperature, specific conductance, dissolved oxygen, pH, oxidation-reduction potential, turbidity, and chlorophyll concentration are measured throughout the water column at up to 30 sites (fig. 1) on the reservoir, with samples for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton being collected at selected sites. Continuous monitoring of Glen Canyon Dam releases for water temperature, specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll concentration and monthly sampling for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton, and zooplankton below the dam and at Lees Ferry, will also be maintained.

Data Access and Availability

The development of a website with online data access capabilities is a necessary component of the Lake Powell monitoring program. Data are already stored effectively in a Microsoft Access database, have been published as a USGS Data Series Report, and are available for download in database and csv format. However, the ability to query selected data, view graphical analyses of these queries, and server other products through an interactive web-based interface is currently lacking. It is proposed that a system with these capabilities be developed and implemented early in the proposal period.

This project would first entail migration of the existing database to an Oracle-based database so that it would be for use by GCRMC staff to provide functionality equal to, or better than the existing database system. Since the existing database is already normalized and fully functional migration is expected to be fairly straightforward and can be accomplished in-house with collaboration provided by the USGS Center for Integrated Data Analytics (CIDA). Migration would consist of the following steps:

1. transferring the contents of each table in the database
2. migrating existing queries, data-entry forms, and reports
3. establishing procedures for incorporation of new data by manual or automated methods
4. developing interfaces to various analytical software tools such as SAS, Surfer, Arc Map, and Microsoft Office products
5. testing and quality assurance verification

To facilitate online access by stakeholders, managers, and other interested users, a website will also be developed that would serve as a primary point of access for information relating to the Lake Powell water-quality monitoring program. This site would allow interactive access to the database in the form of a map-based query system that would serve data from the various components of the monitoring program based on selected locations and time ranges. From these queries, users would be able to retrieve tabular data, statistical summaries of these data, and graphical depictions of depth profiles and the results of chemical and biological sample analyses at various time scales ranging from recent data to the entire historical record.

Data products would include summary graphs and tables showing Lake Powell reservoir elevations and 24-month projections, Glen Canyon Dam release water quality, selected reservoir depth profiles, and isopleth figures displaying temperature, conductivity, dissolved oxygen or other parameters for the entire reservoir at a single point in time or as a time series for a given station.

At its full development, data from other sources would be available on the website, including:

1. reservoir elevation and storage information for other upper and lower Colorado River Basin reservoirs provided by Reclamation
2. streamflow and water-quality information for inflows from tributaries to Lake Powell from the USGS NWIS system
3. other Lake Powell data collected outside the existing GCMRC monitoring program
4. water-quality information collected on other reservoirs such as Lake Mead, Flaming Gorge, Navajo, and other reservoirs provided by Reclamation, Southern Nevada Water Authority, and other agencies or academic institutions.
5. links to other data sources and relevant publications.

The web interface to the data would be accomplished by a combination of in-house work and assistance from the USGS Center for Integrated Data Analytics project will be accomplished in-house, with assistance from CIDA. CIDA has developed similar applications for the GCMRC Sandbar and Sediment Storage (Project A) and

Streamflow, Water Quality, and Sediment programs. Currently there is a sub-allocation of funding to the Wisconsin Science Center for the work of Dale Robertson of approximately $30,000 per year. This funding could be used for initial development of the web interface, depending on the actual distribution of work between CIDA and GCMRC.

Modeling

Simulation modeling of Lake Powell water quality and hydrodynamic patterns is currently being conducted by Reclamation's Upper Colorado Regional Office using the Army Corps of Engineers CE-QUAL-W2 model. The CE-QUAL-W2 model is a two-dimensional (longitudinal and vertical), laterally averaged, finite-difference water-quality and hydrodynamic model for rivers, estuaries, lakes, reservoirs and river basin systems. It was originally known as LARM (Laterally Averaged Reservoir Model), developed by Edinger and Buchak (1975). In its early stages, The LARM model was applied to Lakes Powell and Mead, (Edinger and Buchak, 1982; Edinger and others, 1984). Current model release enhancements have been developed under research contracts between the Army Corps of Engineers and Portland State University under supervision of Dr. Scott Wells (2000). Williams (2007) applied the CE-QUAL-W2 model to Lake Powell and developed an initial dissolved oxygen calibration for the model.

GCMRC provides data and collaboration with the development of the model for calibration and verification. The model has been calibrated and verified to simulate historical patterns of temperature and salinity in Glen Canyon Dam releases. Dissolved oxygen is also being simulated; however, some additional effort is needed for final calibration and verification. This model can be used to synthesize data for periods in which regular monitoring was not conducted and to simulate the effects of various hypothetical operational, hydrological, and climatological scenarios on historical patterns. It is also used to provide predictions of future temperature and dissolved oxygen patterns in Glen Canyon Dam releases. One major shortcoming of the model's predictive capabilities is the lack of adequate input data for inflow water quality and meteorological conditions in the upstream portion of the reservoir. The error in predictive capability decreases substantially with the input of data from reservoir monitoring in the early summer.

Opportunities exist for further understanding of reservoir processes by model development and enhancement. The use of this model, calibrated for temperature, nutrients, and biological components, to reconstruct historical conditions, project future hydrological and climatic scenarios, and simulate the response of the system to hypothetical reservoir operations could help to answer a variety of research questions and gain further understanding of the various hydrodynamic, chemical, biological, and mixing processes in the reservoir.

GCMRC will work on a collaborative basis with Reclamation to calibrate the model for dissolved oxygen, nutrient dynamics, and biological responses under a collaborative system in which current capabilities of the CE-QUAL-W2 model are maintained, while the research-related capabilities of the model, such as the forecasting of low dissolved oxygen concentrations in Glen Canyon Dam releases under reservoir drawdown and identifying factors that affect the fate of inflow currents. It is proposed the model be maintained for its current purposes by Reclamation, with further development by GCMRC, a post-doctoral fellow, or an outside contractor, such as Ed Buchak, who has performed previous work for Reclamation.

Biological Data Analysis

As data from a backlog of plankton samples become available within the next year, a complete history of Lake Powell plankton data, including the initial stages of a quagga mussel invasion, will become available for analysis. When complete, it is proposed that the biological data be incorporated in regular reporting with physical-chemical data. An analysis of these data would include identifying trends in biomass and community structure of zooplankton and phytoplankton populations and identifying potential factors that affect these populations.

Sediment Delta Monitoring

Since 1998, longitudinal sonar depth measurements of the sediment deltas in Lake Powell tributaries have been recorded on thermal chart paper, in conjunction with quarterly reservoir water-quality surveys. Digitization of these charts yields a longitudinal profile of the elevation of the sediment delta with respect to distance along the original river channel. Collectively, these profiles provide a history of Lake Powell sediment deposition during this period, over a range of reservoir elevations and inflow volumes. Information from this record demonstrates sediment transport and deposition processes as affected by inflow currents, underwater landslides, and other channel obstructions and can help to explain unusual water-quality conditions observed in portions of the reservoir.

Digitization of these profiles was initiated in 2012, with the aid of a temporary student intern. Progress has stalled since the departure of that intern and lack of additional staffing. With the addition of a technician to the GCMRC staff, it is proposed that remaining profiles be digitized, compiled, and published as a complete historical record.

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

A. Investigators

David J. Topping, Research Hydrologist, USGS, Grand Canyon Monitoring and Research Center
Ronald E. Griffiths, Hydrologist, USGS, Grand Canyon Monitoring and Research Center
David J. Dean, Hydrologist, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

This proposal is to fund the ongoing required core monitoring of stage, discharge, water quality (water temperature, specific conductance, turbidity, dissolved oxygen), suspended sediment, and bed sediment at gaging stations in the Colorado River Ecosystem (CRe) downstream from Glen Canyon Dam in Glen Canyon National Recreation Area and Grand Canyon National Park. The data collected by this project provide the fundamental stream flow, sediment transport, temperature, and water quality data that are used by other physical, ecological, and socio-cultural resource studies. Thus, this project directly links dam operations to the physical, biological, and sociocultural resources of the CRe. This project also funds interpretation of these basic data, specifically examining how stream flow and its related attributes affect resources of the CRe.

C. Proposed Work

C.1. Project Elements

Much of the proposed work in this project consists of continued high-resolution (typically 15-minute) measurements of the following parameters: stage, discharge, water temperature, specific conductance, turbidity, dissolved oxygen, suspended-sediment concentration, and suspended-sediment grain-size distribution. In addition, episodic measurements of bed sediment are made. These parameters are measured at USGS streamflow gaging stations located on the Colorado River in Marble and Grand Canyons at river miles 0, 30, 61, 87, 166, and 225 (Griffiths and others, 2012). Selection of these gaging-station locations was largely based on the need to resolve longitudinal differences in sediment storage in key reaches of the CRe, to bracket major tributaries, to support other GCDAMP-funded projects, and to reoccupy former USGS streamflow-gaging stations where stage, discharge, water quality, and sediment-transport data were previously collected. In addition, high-resolution stage, discharge, water temperature, suspended-sediment concentration, and suspended-sediment grain-size distribution are measured at sites in all of the major tributaries to the Colorado River and in a representative subset of the smaller, and formerly ungaged, tributaries to the Colorado River (Griffiths and others, 2010, in press). All measurements of stage, discharge, water quality, and all physical measurements of suspended- and bed sediment are made using standard, approved USGS techniques. Errors in conventional suspended-sediment measurements are calculated using the methods of Topping and others (2011) and Sabol and Topping (2013). The laser diffraction and acoustic measurements of suspended sediment are made using techniques described in Melis and others (2003), Topping and others (2004, 2006a, 2007b), and Wright and others (2010c).

The funding requested under this proposal only partially covers the costs of data collection at the USGS gaging stations where data are collected to support GCDAMP goals. Some of the gaging stations on the Colorado River and its tributaries receive substantial amounts of funding from non-GCDAMP sources, thus their locations are partially dictated by non-GCDAMP goals. For example, gage height and discharge data collected at the gaging stations on the Colorado River at Lees Ferry, AZ, (09380000), and above Diamond Creek near Peach Springs, AZ, (09404200) are entirely funded from non-GCDAMP sources. In addition, gage height and discharge data collected at the gaging stations on the Paria River at Lees Ferry, AZ, (09382000), the Little Colorado River near Cameron, AZ, (09402000), and on the Colorado River near Grand Canyon, AZ, (09402500) are heavily subsidized by non-GCDAMP sources. Finally, all of the personnel listed on this project receive parts of their salary from non-GCDAMP sources.

The most significant product from this project during FY 2013-14 has been the development of the website on which we serve project data and serve user-interactive sediment budgets: http://www.gcmrc.gov/discharge_qw_sediment/. The user-interactive sediment budgets found on this website are currently being used to design HFEs. During FY 2015-17, we propose to continue to serve project data and user-interactive sediment budgets through this website. In addition, work will continue to add additional data streams to this website and expand the user-interactive tools. Chief among the new tools to be developed are user-interactive duration curves. Duration curves are one of the most useful and powerful tools for conveying complicated hydrologic and water-quality datasets. We have successfully used duration curves to analyze changes in stage, discharge, and turbidity for various periods and reaches in the CRe (Topping and others, 2003; Voichick and Topping, in press). Once the duration-curve tool is added to the website, the user will be able to plot the percentage of time any parameter served on our website is equaled or exceeded for any user-specified period.

All database and website work has been made possible through collaboration with the USGS Center for Integrated Data Analytics. The Center for Integrated Data Analytics (CIDA) is the leader within the USGS in database and web programming. Collaboration with CIDA has resulted in a major leap forward in serving data in a user friendly and interactive way, something that has proven problematic for GCMRC to do on its own in previous funding cycles. The tools developed in collaboration with CIDA are allowing anyone to plot the data, construct mass-balance sediment budgets, and plot changes in reach-averaged bed-sediment grain size for any time period in any reach of the CRE on demand. In addition, these tools allow different user-chosen methods for error propagation through these sediment budgets. Because sandbar response during controlled floods depends on both the amount and grain-size distribution of the sand stored in each reach (Topping and others, 2006b, 2010), these tools have proven to be extremely useful in the planning of controlled floods under the HFE protocol EA (U.S. Department of the Interior, 2011) and will inform monitoring under the LTEMP EIS.

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 interpretations in peer-reviewed articles in the areas of hydrology, water quality, and sediment transport. These papers are designed to answer key questions relevant to river management, especially to managers in the GCDAMP (see proposed publication list below). The data collected in this project form the basis of the collaborations listed in the next section. All of the projects funded in the areas of physical science, biology, and socioeconomics require the data collected by this project. During FY 2015-17, multiple journal articles and top-tier USGS reports will be published on the following topics:

- Analysis of Paria River and Little Colorado River hydrology 1920s-present with implications for long-term sediment management in the CRe (lead author Topping)
- Geomorphology, hydraulic geometry, and sediment transport in the Paria River (lead author Topping)
- Analysis of a decade of measurements of sediment transport in the lesser tributaries: Do the lesser tributaries matter? (lead author Griffiths)
- Linkage between hydrology, sediment transport, and geomorphic change in the Little Colorado River, with implications for aquatic and riparian habitat in the lower Little Colorado River (lead author Dean)

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

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

A. Investigators

Paul Grams, Research Hydrologist, USGS, Grand Canyon Monitoring and Research Center
Daniel Buscombe, Research Geologist, USGS, Grand Canyon Monitoring and Research Center
Erich Mueller, Research Geologist, USGS, Grand Canyon Monitoring and Research Center
Joel Sankey, Research Geologist, USGS, Grand Canyon Monitoring and Research Center
Joseph Wheaton, Assistant Professor, Utah State University
Brandon McElroy, Assistant Professor, University of Wyoming
Mark Schmeeckle, Professor, Arizona State University
David Rubin, Research Geologist, USGS, Coastal and Marine Geology
Ted Melis, Physical Scientist, USGS, Grand Canyon Monitoring and Research Center
Joseph E. Hazel, Jr. and Matt Kaplinski, Research Associates, Northern Arizona University
Keith Kohl, Surveyor, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

This proposal describes a set of integrated studies that are collectively designed to track the results of individual High-Flow Experiments (HFEs), monitor the cumulative effect of HFEs and intervening operations, and advance understanding of sediment transport and eddy sandbar dynamics to improve capacity for predicting the effects of future dam operations. Management of the Colorado River downstream from Glen Canyon Dam requires that managers balance objectives related to sediment conservation with other management objectives, and do so in the context of a limited supply of fine sediment. Evaluation of whether management goals are being met currently and prediction of the likelihood of meeting goals in the future requires a combination of monitoring activities and research efforts.

The key uncertainty about management of sandbars downstream from Glen Canyon Dam that is articulated in the December 2011 *Environmental Assessment for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam,* is 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?" Although the *Long-term Experimental and Management Plan Environmental Impact Statement* is not yet complete, the fundamental sediment-related question is essentially the same for this plan which addresses all aspects of dam operations including HFEs. The overarching goal of this project is to address this question through continued monitoring of sand deposits over multi-year periods that included repeated controlled flood experiments.

Monitoring conducted in this project will include daily and annual observations of long-term sandbar monitoring sites by remote camera and conventional topographic survey, respectively. These observations add to the existing long-term dataset and will be available following each HFE as an initial assessment of resource condition that could be used to adjust the HFE implementation strategy, if necessary. Because these monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, this project also includes the analysis of system-wide airborne remote-sensing data to monitor a much larger set of sandbars to assess sandbar size and abundance at intervals of every 4 years or greater.

The continued success of HFEs to rebuild sandbars depends on maintaining an adequate supply of sand in the bed and banks of the Colorado River. If there is a decline in sand storage, the likelihood that HFEs alone can maintain sandbars is decreased. While the sandbar monitoring studies provide needed information on resource condition, they do not provide any measure of the total amount of sand in storage in and near the Colorado River, because a very small fraction of the sand in storage is in the monitoring sites. To provide this critical information about sand storage and to evaluate whether dam operations, including HFEs, are likely to result in sandbar maintenance or eventual decline, sediment storage will be monitored by repeat channel-wide surveys of river segments on a rotating basis of approximately every 3 to 10 years.

This project also includes 3 research and development components: methods for acquiring rapid and low-cost sandbar surveys, investigation of bedload processes, and development of a new sandbar response model. These projects are designed to improve monitoring methods, improve estimates of sand transport, and develop new tools for predicting how management actions affect resources. Collectively, these studies will contribute to improved capacity to predict the effects of future controlled floods.

C. Proposed Work

This project is divided into 4 monitoring and research elements and one additional support element. The first two project elements are monitoring projects, each with some research aspects that address monitoring needs. The latter two elements are research projects that contribute to improving the monitoring program and improving predictive capacity. Research element A.3 will continue the investigation on physical controls on variability in sandbar deposition with the goal of developing a new model for sandbar response to flow and sediment conditions. The objective of research element A.4 is to develop an improved estimate for the contribution of bedload transport to total sand flux. This will improve our ability to estimate sand mass balance and reduce the uncertainty in those estimates. The control network and survey project element supports the other project elements, as well as other GCMRC projects.

The ultimate measure of whether or not fine sediment is conserved in and near the Colorado River is the increase or decrease in volume and area of fine sediment deposits. Thus, monitoring elements involve repeat measurements of topography such that changes in the volume of sand deposits can be calculated. Because the management focus is on fine sediment, it is necessary to discriminate sand and finer sediment from gravel, cobbles, and boulders. In order to more effectively detect change in different resources of importance, it is necessary to monitor change in sand storage at both high and low elevations. This requires a mix of direct field measurement, remote sensing, and extrapolation throughout the 255 miles of the Colorado River between Glen Canyon Dam and River Mile 240, which is the upstream end of Lake Mead reservoir.

Data collection efforts occur across a wide range of spatial and temporal scales (Table 1) in order to detect change in a very large system in which significant change is often local and episodic. At a select set of long-term monitoring sites, sandbar monitoring is conducted at a daily (using remote cameras) and annual (by conventional survey) interval in order to track local response to individual events in the context of a long-term record. A larger collection of sandbars are also monitored using remote sensing, in order to provide a synoptic view of the entire Colorado River.

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

Project Element	Spatial Focus	Method	Measurement Frequency	Information Needs Met
A.1	Selected high-elevation sandbars (47 sites)	Conventional topographic surveys (volume and area)	Yearly	Annual status check on sandbar and camping beach condition
A.1	Selected high-elevation sandbars (42 sites)	Remotely deployed digital camera (approximate size)	Daily	Status check on sandbar condition at ~6-month intervals
A.1	High-elevation sandbars systemwide (>1000 sites)	Remote sensing (area)	Every 4+ years*	Long-term trend of sandbar condition
A.2	Low-elevation fine sediment storage in 30 to 80-mile segments.	Combined bathymetric and topographic surveys (area and volume)	Every 3 to 10 years, depending on reach.	Long-term trend in fine sediment storage

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

Monitoring of fine sediment deposits is also conducted at multiple scales using a variety of methods. Sediment inputs and outputs (the I and O terms in equation 1) are monitored at a daily scale in 30-mile or longer sediment budgeting reaches (Project 2: Streamflow, Water Quality, and Sediment Transport). In this project, we monitor changes in sediment storage directly (the ΔS term in equation 1) at approximately 3- to 10-year time intervals and with very high precision. These monitoring strategies are complementary. The mass balance measurements of high temporal resolution can be used to track tributary inputs and to schedule high flows. Fine sediment storage monitoring provides a direct measurement of changes in storage for all storage environments over the entire monitoring period, whether a few years or several decades.

C.1. Project Elements

Project Element 3.1. Sandbar Monitoring

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

Paul Grams, Research Hydrologist, USGS/GCMRC
Daniel Buscombe, Research Geologist, USGS/GCMRC
Joseph Hazel and Matt Kaplinski, Research Associates, Northern Arizona University
Bob Tusso, Hydrologist, USGS/GCMRC

Objectives

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

Hypotheses/Questions

1. What is the cumulative effect of HFEs and intervening dam operations on the size of sandbars in the CRe?
2. Do individual HFEs continue to build sandbars with the same effectiveness observed in response to previous HFEs?
3. Do individual sandbars respond differently to different HFEs?
4. How does sandbar size and shape prior to HFEs affect the bar-building response?

Methods

Sandbar and campsite surveys will be conducted each fall using established methods (Hazel and others, 2010; Kaplinski and others, 2014). The methods for the proposed rapid surveys and modeling are described below under projects A.1.3 and A.1.5, respectively. The novel methods that will be developed and used in this project element are those associated with the effort to quantify sandbar area and volume from the remote camera images.

Essentially, the process of estimating sandbar areas consists of orthorectifying oblique images using surveyed ground control points, then delineation of the sandbar on each orthoimage, and finally calculating the area. The technique has been demonstrated using time-series of images from the 22-mile and 30-mile sandbars. The sandbars have been identified manually and this process has already added hundreds of areal estimates spanning up to the last 5 years, verified using ground based surveys. As well as collecting more ground control points during channel mapping survey campaigns, we propose to make the process of sandbar delineation from images as automated as possible, because the process must be repeated many times at each of the monitoring sites. To this end, initial trials using a variety of image processing methods have been highly encouraging, so we are confident that accurate, automated delineation of sandbars from images is feasible. This technique has the potential to massively augment data on subaerial sandbar areas, at minimal extra cost, at a number of important sites, in the recent past and in the future.

We have recently demonstrated that sandbar volumes can also be estimated from digital elevation models (DEMs) constructed directly from orthorectified digital imagery from autonomous cameras. If the elevations of water lines in images are known, contour maps of sandbars can be constructed as the flow varies. The process consists of obtaining the horizontal coordinates of waterlines from the rectified image, and assigning the vertical coordinate from the estimated water stage. As the stage varies, a DEM can be constructed from several contour lines.

The process works best if stage varies significantly over short periods, such as during controlled floods. Stage elevations are either measured using an instrumented record (such as a pressure transducer) or estimated using a stage-discharge relationship (which exist for all long-term monitoring sites; Hazel and others, 2006). The technique has been trialed using imagery from 30-mile sandbar during the 2012 and 3013 HFEs. The DEM constructed using imagery from the 2012 HFE was validated using data collected at that site immediately afterwards using conventional ground-based surveys. We propose to apply the technique to more sites to obtain volumetric estimates of bars after HFEs, as a very cost effective means with which to assess the effects of HFEs on sandbars.

Outcomes and Products – FY2015

- Presentation at annual reporting meeting on the status of sandbars and campsites based on monitoring from the previous year.
- Web browser interface for viewing remote camera photographs.
- Web browser interface for viewing sandbar data.
- Journal article detailing and evaluating methods for measuring sandbar areas and volumes from remote camera images.

Outcomes and Products – FY2016

- Presentation at annual reporting meeting on the status of sandbars and campsites based on monitoring from the previous year.
- Sandbar data and photographs updated on web interface.
- Report/journal article on sandbar response to HFEs or short-term sandbar variability based on measurements of sandbar size derived from remote camera images.

Outcomes and Products – FY2017

- Presentation at annual reporting meeting on the status of sandbars and campsites based on monitoring from the previous year.
- Sandbar data and photographs updated on web interface.
- Report/journal article on long-term trends at the sandbar monitoring sites.

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

Joel Sankey, Research Geologist, USGS/GCMRC
Rob Ross, Hydrologist, USGS/GCMRC
Ted Melis, Physical Scientist, USGS/GCMRC
Paul Grams, Research Hydrologist, USGS/GCMRC
Tom Gushue, Computer Specialist, USGS/GCMRC

Objectives

The primary objective of this work is to measure the area of exposed sand above the elevation of the 8,000 ft^3/s stage (high-elevation sand) for more than 1300 large eddies along the Colorado River using imagery acquired from the remote sensing overflight in May 2013. The results from mapping sand area on the 2013 images will be compared with sand area measured on the 2002 and 2009 images (Ross and others, in prep.).

A secondary objective of this work is to evaluate the extent to which topographic changes above 8,000 ft^3/s can be detected and monitored with the 2002-2009-2013 time series of digital topography (DSM, digital surface models) from automated photogrammetry that is acquired coincident with overflight imagery. We will evaluate the utility and limitations of these data to monitor topographic changes in units of high elevation sand mapped in the first objective, as well as localized shoreline changes due to activity of individual tributaries that produced coarse-grained sediment deposits visible above 8,000 ft^3/s. The secondary objective will focus on Marble and Eastern Grand Canyon.

In addition, this project will include the completion of a geomorphic base map for all of Grand Canyon. The geomorphic base map will be used by this and other projects that require information about the distribution and characteristics of eddies, sandbars, debris fans, gravel bars, and other geomorphic units throughout the entire Colorado River corridor.

Hypotheses/Questions

Mapping Sandbar Area

1. Are the increases in sandbar area observed between 2009 and 2013 at the long-term monitoring sites representative of changes over that same period for sandbars throughout Marble and Grand Canyons?
2. Are there longitudinal (downstream) variations in sandbar response?

Measuring Topographic Changes in Sandbars and Debris Fans

1. Can topographic changes associated with 1) erosion or aggradation of sand within eddies and above 8,000 ft^3/s, or 2) coarse-grained tributary sediment deposits, be detected from available digital topography data in Marble and Eastern Grand Canyons?, and if so, then can such terrestrial changes be related to aggradation of nearshore or deeper channel area offshore below the 8,000 ft^3/s stage from existing bathymetric data?
2. Do areal or topographic changes associated with 1) erosion or aggradation of sand within eddies and above 8,000 ft^3/s, vary as a function of 2) coarse-grained tributary sediment deposits at locations in Marble and Eastern Grand Canyons?

Geomorphic Base Map

1. What is the number, spatial distribution, and extent (area) in the CRe of:
    a. eddies that contain or may contain sandbars in the CRe;
    b. channel-margin sand deposits not within eddies;
    c. gravel bars; and
    d. debris fans?

Methods

Mapping sandbar area

In the FY 13/14 work cycle, regions historically containing exposed sand above the elevation of the 8,000 ft^3/s stage (high-elevation sand) were delineated for more than 1300 large eddies along the Colorado River in imagery acquired in 2002 and 2009. Current work conducted in the FY 13/14 cycle is classifying the areas of sand exposed in the 2002 and 2009 imagery (Davis, 2012), which will then be extracted from the more than 1300 regions of potential significance from river mile (RM) 0 to ~ RM 276. In lieu of analyzing the 1988 imagery for selected reaches, a set of geomorphic maps compiled by Utah State University researchers over six reaches (Schmidt and others, 2004) were used to map high-elevation sand in 1965, 1973, 1984, 1990, and March and April of 1996; the April 1996 maps were updated with photogrammetrically-derived shorelines from 2002, 2005, and 2009 imagery. Results of the work conducted during the FY 13/14 cycle will be delivered and summarized in a manuscript prepared for the end FY 2014 (Ross and Grams, in preparation), and work on the canyon-wide analysis for 2002, 2009, and 2013 will be in preparation from FY 14-17.

The new work proposed in this prospectus will extend analyses conducted on the 2002 and 2009 imagery to include measurements of sand area in imagery acquired in the 2013 overflight. The canyon-wide remote sensing data used in this effort consists of (1) four-band, orthorectified digital imagery (blue, green, red, and near-infrared bands) acquired in late May, 2013. The remote sensing effort will involve a landscape delineation of four units: water, vegetation, sand, and other bare (non-vegetated) terrestrial surfaces. This will be similar to the landscape databases in production for image data sets collected in 2002 and 2009. For each image set, the water surface and total vegetation are mapped using interactive image processing algorithms (Davis et al., 2002; Ralston et al., 2008). This project will use water and total vegetation classifications produced for the 2013 imagery in riparian vegetation-related project work that is currently proposed to be conducted in FY 2015. Following the water and vegetation classification, areas of sand will be classified. Therefore the sand area classification and measurements proposed here will commence in FY16 and proceed into FY17. The results of the mapping and change analyses will be reported on in FY17.

Measuring topographic changes

Digital surface models (DSMs) were produced from airborne automated digital photogrammetry data acquired during the aerial overflights of 2002, 2009, and 2013 for the 450 km length of Glen and Grand Canyon at steady Colorado River discharge of 227 m^3/s (8,000 ft^3/s) (Davis, 2012). The airborne automated digital photogrammetry DSM data acquired in 2002 and 2009 have been evaluated during work recently completed in 2013 and 2014 by Phil Davis (personal communication). The DSM data have 1-m cell resolution with vertical ellipsoid heights reported to the nearest 10 cm (but only accurate to the nearest 30 cm – see following explanations and example of error assessment for the 2009 data), and are sectioned into U.S. Geological Survey map quadrangles. The data were not initially processed to remove effects of vegetation or other surface cover on topographic elevation values. However, recent work completed in 2013 and 2014 developed a methodology to minimize these effects that was tested on the 2009 dataset, in which pixels that contained vegetation canopies identified in classification of the coincidentally collected and co-registered multispectral imagery, were replaced with elevations interpolated from surrounding bare ground surfaces.

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

For this objective we will conduct a change detection using the digital topography (DSM) data from 2002, 2009, and 2013 overflights acquisitions. The change detection will be completed for Marble and Eastern Grand Canyon segments of the river corridor and will be segregated by geomorphic unit using the completed geomorphic base map. The datasets will be differenced and vertical and volume changes will be estimated for the areas of sand mapped in the large eddies that are the focus of objective one. Changes that are detected in these areas will be evaluated relative to ground truth, as available, from the subset of sandbars that topographically surveyed. Changes will also be estimated for the differenced datasets within the mouths of tributary channels and debris fans throughout Marble and Eastern Grand Canyon including those respectively associated with the individual large eddy areas that are the focus of objective one. Coarse-grained inputs from tributaries can alter the physical influence of individual debris fans on river hydraulics, potentially leading to changes in the characteristics of eddies, which in turn might result in changes to deposition and erosion of sand. Therefore, we will evaluate whether physically meaningful, statistical relationships exist between areal or topographic changes detected for sand and topographic changes attributed to coarse-grained tributary sediment deposits above 8,000 ft^3/s at locations in Marble and Eastern Grand Canyons. Following after the previous work of Melis and others (1995), Webb and others (2000), and Griffiths and others (2004), we will update prior inventories of tributaries that have produced debris flows in Grand Canyon National Park, and also develop a new, but related inventory of tributary confluence area that have been topographically altered by deposition of streamflow derived gravels, or eroded by tributary flash floods.

Several significant tributary streamfloods and debris flows are known to have occurred during the proposed remote sensing monitoring period. Three tributaries known to have produced debris flows since 2009 include: Cathedral Wash, Red Canyon, and National Canyon, located at river miles 2.8-R, 76.7-L and 166.4-L, respectively. Because these tributaries are located in upper Marble Canyon, Eastern and Central Grand Canyon, and have drainage areas of 17.3, 10.5, and 407.1 km^2 they represent widely ranging catchment characteristics (lithologies, drainage aspect and median elevations) throughout Grand Canyon that are related intense rainfall and debris flow potential (Griffiths and others, 2004). The stage-discharge rating at GCMRC's monitoring streamgage located upstream of National Canyon (river mile 166.4-L) was apparently affected by the summer 2012 debris flow and streamflooding. The debris flows at Red Canyon about a month later was reported to have significantly altered Hance Rapids, particularly the upper-left side entrance to the rapids and is likely the first debris flow to have occurred in that tributary since the late 1890s (Webb, 1996; Melis and others, 1995). Cathedral Wash produced a debris flow in September 2013, that is also believed to be the first such event in that drainage since the late nineteenth century, and the 2013 DSM can also provide a base reference topographic surface of the debris fan at that confluence; one that might then be compared to a local instrument survey to document the local changes there, such as the drop through Cathedral Rapids. On the basis of sandbar monitoring data collected at a river-left study site upstream from Cathedral Rapids in October 2013, the stage-discharge rating curve in the upper pool (Hazel and others, 2010) was elevated by approximately 1.5 ft. (J. Hazel, Northern AZ University, preliminary data, 2013).

In addition, gravel deposits delivered by streamflooding associated with intense rainfall in September 2011, was reported by members of the sandbar survey crew near river mile 30 in Marble Canyon (J. Hazel, Northern AZ University, 2011), and these inputs were later reported to have at least temporarily altered the discharge-stage rating at the 30-Mile streamgage located upstream. Other areas of Marble Canyon were also likely affected by the September 2011 storms and evaluation of the 2009 and 2013 DSMs provide an opportunity to identify tributary confluences that may have been similarly aggraded with stream gravels. Shoreline changes detected from evaluation of the 2009 and 2013 DSM will also focus further evaluation of channel-geometry changes offshore below 8,000 ft3/s stage in segments where repeat bathymetric data sets are available. Lower Marble Canyon data from channel mapping in May of 2009 and 2012, and data from Eastern Grand Canyon collected in spring 2011 and 2014 may be used for this analysis in 2015-16. Channel data for Upper Marble Canyon were collected in spring 2013, so that additional coverage of that segment might be available for assessing changes from gravel inputs after that Marble Canyon segment is remapped after 2015. During 2015-16, the task of integrating lesser tributary drainage polygons with the GCMRC river centerline dataset will also be undertaken by Melis and Gushue.

Geomorphic base map

The geomorphic base map will be conducted by identifying contacts between each of the map units and digitizing those lines on-screen in ArcGIS. The initial interpretation and mapping will be done in the office using recent (2009) aerial imagery as a base. The preliminary mapping will followed by field checking areas of uncertainty on the annual sandbar monitoring trip in Fall 2015, requiring no additional logistic costs. Grams (unpublished data) has completed a preliminary base map for lower Marble Canyon (Figure 1) for use in the channel mapping project (FY 13-14 Project A.2).

Outcomes and Products – FY2015

- Completed geomorphic base map.
- Report/journal on geomorphic base map.

Outcomes and Products – FY2016

- Report/journal article on changes coarse-grained deposits.

Outcomes and Products – FY2017

- Report/journal article on system wide changes in sandbar area and sandbar elevation from remote sensing, 2009-2013.

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

Joseph Wheaton, Assistant Professor, Utah State University
Daniel Buscombe, Research Geologist, USGS/GCMRC
Paul Grams, Research Hydrologist, USGS/GCMRC
Graduate Student

Objectives

1. Develop, evaluate and implement a methodology which allows low-cost and rapid (in terms of data collection and processing) monitoring of sandbars with a camera.
2. Evaluate the use of ‘structure-from-motion’ (SfM), a photogrammetric technique which can build an accurate three-dimensional surface model from photographs of a scene taken from multiple viewpoints (James and Robson, 2012; Westoby and others, 2012; Fonstad and others, 2013), for mapping the elevation of sandbar surfaces, including quantifying errors and uncertainties, and the logistical considerations of efficient field data collection.
3. Design, implement, and evaluate a set of sampling and data-processing protocols for creation of repeat digital elevation models (DEMs) of sandbars, on a common control

network, from a set of photographs taken inexpensive cameras to support monitoring and geomorphic change detection.

4. Acknowledging that the technique, if objectives 1 through 3 are met, could lend itself to opportunistic sampling (on any river trip), develop 'citizen science' tools by which boatmen and members of the public, with limited instruction through a public website, could contribute to sandbar mapping efforts in Grand Canyon simply by taking a set of controlled photographs.
5. Use SfM-created DEMs over a larger sample size (i.e. > 100’s of bars) to augment and evaluate the representativeness of the 45-50 long-term NAU sandbar time-series (see hypotheses/questions below).
6. Because SfM creates ‘point clouds’ of geo-referenced elevations and colors, scope the feasibility of SfM for mapping vegetation canopy elevations and three-dimensional structure.

Hypotheses/Questions

1. Can accurate digital elevation models (DEMs) be obtained rapidly, with quantification of errors and uncertainties, and with minimal logistical support, using a consumer-grade camera? Assuming they can, what are the limitations of this technique relative to traditional total station surveys and what is the relative accuracy of SfM-derived DEMs compared to total station derived DEMs.
2. Can a simple protocol forthe photography of any sandbar, be followed by a non-specialist, which would produce sufficient quality data to create a reliable DEM of that sandbar from SfM?
3. What set of metrics encapsulate the essential changes to a sandbar over time using repeat SfM mapping? How can these metrics be combined to assess the state/health, persistence and/or dynamism of any given sandbar over time?
4. What information about vegetation can be pulled from raw point clouds obtained by SFM? Acknowledging that vegetation creates ‘noisy’ clouds of geo-referenced elevations, the ‘raw’ point cloud is distinguished from the ‘processed’ version used for smooth surface estimation obtained using interpolation methods, and requires different mathematical tools for analysis. These tools, developing primarily in the field of LiDAR data processing, operate on the point clouds themselves rather than gridded surfaces.
5. How does generalized sandbar morphology differ as a result of high flows with different hydrograph shapes (magnitudes, durations and asymmetries)? Specifically, does high flow downramp rate affect sandbar slope? Answering this question requires more frequent data from sandbars at sites with a range of hydraulic and geological settings, hitherto unobtainable due to a technological shortfall that will be addressed with the SfM technique.

Methods

The majority of the work will be carried out by a graduate student at Utah State University under the primary supervision of Joseph Wheaton, seconded by Paul Grams and Daniel Buscombe at GCMRC.

The student will familiarize him/herself with powerful, and expansive (scriptable), commercial SfM software (e.g. Agisoft Photoscan) as well as open-source software implementations of SfM (e.g. VisualSfM); carry out a number of trials in controlled conditions in order to assess the accuracy and precision of digital surface models; and develop protocols for photo collection such as, but not limited to, 1) the number and angular spread of images; 2) the requirements for vantage and perspective; 3) the degree of overlap between images; 4) the minimum amount of ground control points required, and 5) the effects of light conditions and surface textures on the photogrammetric solution. The student will then systematically image sandbars in Grand Canyon during annual sandbar monitoring trips, during which time the same bars will be mapped using conventional total station surveys. A subset of bars will also be surveyed with similarly high resolution, but higher precision ground-based LiDaR as a means of quantifying the accuracy of SfM. This data will be worked up into image-derived and conventional DEMs, and the accuracy of the SfM technique for sandbars will be assessed through extension of surface uncertainty estimation techniques in the GCD software.

One potential challenge associated with photogrammetric mapping of sandbars in Grand Canyon is the effect of strong sunlight and shadows, which may limit the success of SfM at pixel matching in areas of low contrast. This will be tackled directly by collecting images of the same bar from the same locations at several times during the same day. Another problem will be obtaining sufficient vantage to photograph from, so each bar will be photographed from a number of different relative elevations and viewpoints. Each set of images will be worked up and their accuracy assessed reference to benchmark data (e.g. total station and ground-based LiDAR surveys). To address the potential issue of insufficient image texture over the smoothest surfaces, the texture of these surfaces will be enhanced using a number of standard camera settings and image processing algorithms designed to enhance image contrast.

Outcomes and Products – FY2015

- Presentation at annual reporting meeting on project progress.

Outcomes and Products – FY2016

- Presentation at annual reporting meeting on project progress.
- Report/journal article on application of SfM method to measuring sandbar topography.
- SfM Sampling Protocol

Outcomes and Products – FY2017

- Presentation at annual reporting meeting on project progress.
- Report/journal article on sandbar topographic change measured by SfM.
- SfM Extensions to GCD and existing SfM software as well as Stand-Alone software required to facilitate efficient post-processing of imagery and change detection analysis.

Project Element 3.1.4. Analysis of historical images at select monitoring sites (from FY2013-14)

Joseph E. Hazel, Jr., Research Associate, Northern Arizona University
Thomas M. Gushue, GIS Coordinator, Grand Canyon Monitoring and Research Center
Robert Weber, Photogrammetrist, Pinnacle Mapping Technologies, Inc.

Objectives

1. Extend sandbar area and volume long-term monitoring measurements to include data points from 1984 for a select set of sites.

2. Interpret the sandbar area and volume measured from photogrammetrically-derived topography with regard to high-flow experiments (HFEs) occurring prior to October 1984, and in the context of measured sandbar response to HFEs since 1990.
3. Incorporate completed 1984 sandbar data into sandbar database and interactive website (Project Element **A.1.1**).

Hypotheses/Questions

1. What is the effect of dam operations on a subset of the long-term monitoring sites after the largest geomorphic event (the 1983 flood) following closure of Glen Canyon Dam in 1963 and prior to the beginning of surveying efforts in 1990?
2. What can the 1984 post-HFE area and volume measurements for a select set of sites inform us about sandbar behavior?
3. Can analysis of digital photogrammetry improve our understanding of sandbar change over time and improve analysis of the long-term monitoring record?

Outcomes and Products

For each completed site:

> **Spatial Data**: Geodatabase Feature Class and Shapefiles for Ground Control Points and Digital Terrain Model (DTM) point clouds, Triangular Irregular Network (TIN) 3D surface derived from point cloud, 25-cm interpolated surface derived from TIN (in Grid and Raster format), and a mosaicked, orthorectified image file of 1984 imagery. ArcMap document containing all related data sets, 3D model containing TIN, raster and orthophoto data sets, an exported ASCII text file of each DTM point cloud, and a catalog of unrectified 1984 image frames used for each site.
> **Ancilliary data**: Photogrammetry block file and triangulation reports, DTM extraction report, Vertical and Horizontal Accuracy Assessments of final data sets (DTM and Orthophotos), volumetric and cross-sectional comparison graphs, and summary reports containing all the above information for each site.

Final Report/journal article in FY17 on historical sandbar condition for all sites processed.

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

Paul Grams, Research Hydrologist, USGS/GCMRC
Daniel Buscombe, Research Geologist, USGS/GCMRC
Matt Kaplinski and Joseph Hazel, Research Associates, Northern Arizona University
Bob Tusso, Hydrologist, USGS/GCMRC
Michael Yard, Fishery Biologist, USGS/GCMRC

Objectives

1. Complete the first (baseline) high-resolution map of Glen Canyon (RM -15 to RM 0) in 2015, with a coverage of 80% or greater.
2. Complete the first (baseline) high-resolution map the long reach from RM 166 to RM 225 in 2016, with a coverage of approximately 50%.

3. Complete a repeat map the long reach from RM 0 to RM 30 in 2017, with a coverage matching that when the reach was first mapped in 2013 (approximately 80%).
4. Implement recently developed acoustic bed-sediment classification methods from multibeam data, by factoring in grain size in estimates for changes in sand storage, and in order to better constrain uncertainties in calculated sediment budgets.
5. Report on changes in sand storage in the reach between RM 60 and RM 87, mapped in 2011 and repeat mapped in May 2014 (scheduled).
6. Report on changes in bed elevation in Glen Canyon based on comparing cross-sections last surveyed in 2000 with the data from mapping that is scheduled for 2015.
7. Continue development of methods for classification of bed sediments using multibeam backscatter data. In particular, develop means to classify bed sediments reliably in the presence of significant coverages of submerged vegetation.
8. Develop and implement methods to estimate sand thicknesses below the bed surface, non-intrusively (using acoustics) and which fit into existing channel mapping sampling design and protocols.

Hypotheses/Questions

1. Are management objectives for fine sediment conservation being met?
    - Do dam operations (HFEs and intervening operations) result in net sediment depletion or accumulation, on a reach scale?
2. Where are locations of the major changes in sand storage? What is the relative proportion of storage change in the channel and eddies?
3. How do we develop a sampling design that requires repeat mapping of a smaller proportion of the river channel area?
4. Can we remotely sense the identity and distribution of submerged aquatic vegetation using hydroacoustics (multibeam sonar backscatter and topography)? If so, can we reliably distinguish between vegetation and sediments?
5. Is it possible to remotely sense submerged sand thicknesses using acoustics, reliably and objectively, in order to better quantify absolute sand storage in the parts of the channel always submerged?

Methods

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

Table 2. Long sediment budgeting reaches for long-term monitoring of sediment storage.

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

* The number of short reaches 2 to 5 km in length that were mapped at least once between 2000 and 2005 (Kaplinski and others, 2009).
** The number of cross-sections that were measured at least once between 1992 and 1999 (Flynn and Hornewer, 2003).

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

Upon completion of a repeat map of a segment, the DEMs will be compared to compute the net change in the volume of sediment within the segment. These computations will distinguish between fine and coarse sediment using recently developed acoustic sediment classification algorithms (Buscombe and others, in review), between sediment stored in the channel and eddies, and between sediment at high- and low-elevation. The methods of Buscombe and others (in review) uses multibeam sonar backscatter (echo strengths) to distinguish between homogeneous sand, mixed sand and gravel, and homogeneous gravel. These data are collected in conjunction with soundings used to compute bathymetries, therefore no additional data collection is required. The resulting maps of bed sediment substrates are as highly resolved as the bathymetric maps. Methods for bed-texture classification will continue to be developed in order for us to reliably distinguish between different substrate types (such as the relative proportions of sand and gravel in small areas), in order to make assessments of their relative mobility under a range of flows.

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

Ongoing analysis between sediment stored in the channel and eddies, and between sediment at high- and low-elevation, will incorporate more sophisticated estimates of uncertainty (e.g. Wheaton et al., 2010; Kaplinski and others, 2014) for which estimates of bed sediment grain size will also be a crucial component. In addition to making comparisons between years for which the entire segments are mapped, comparisons will also be made to earlier data where available (Grams and others, 2013). This will include comparisons to data collected in short reaches in 2000 to 2005, and data collected at monumented channel cross-sections (Table 2).

In 2016 and 2017 we will trial the use of sub-bottom, low frequency (a few kilohertz), acoustic profilers to scope the feasibility of determining sand thicknesses below the bed. A number of different systems are available for rent, incorporating relatively recent technological advances such as frequency modulation (FM, such as CHIRP systems). These sonar provide much greater resolution than previous generations of sub-bottom sonars, providing unparalleled detail on the sedimentary sequences down to several tens of meter. We propose to use these systems in areas of known sandy bed surfaces, and develop algorithms to detect sedimentary layers and acoustic attenuations with depth, towards an eventual goal of reliably estimating sand thicknesses.

Outcomes and Products – FY2015

- Presentation at annual reporting meeting.
- Report and maps for RM 0 to 30 (mapped in 2013).
- Report and maps for eastern Grand Canyon (RM 61 to 87, mapped in 2011 and 2014).
- Report/journal article on geomorphic changes in eastern Grand Canyon, 2011 to 2014.
- Report/journal article on incorporating spatially explicit, high resolution, bed sediment maps in calculations of morphologic based changes in reach-scale sediment storage

Outcomes and Products – FY2016

- Presentation at annual reporting meeting.
- Report and maps for Glen Canyon (scheduled to be mapped in 2015).
- Report/journal article on geomorphic changes in Glen Canyon, 2000 to 2015.
- Report/journal article on acoustic detection of submerged aquatic vegetation.

Outcomes and Products – FY2017

- Presentation at annual reporting meeting.
- Report and maps for west-central Grand Canyon (RM 166-225) (scheduled to be mapped in 2016).
- Report/journal article on long-term trends at the sandbar monitoring sites.
- Report/journal article on the use low frequency sonars to estimate sand thicknesses below the surface.

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

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Mark Schmeeckle, Professor, Arizona State University
Daniel Buscombe, Research Geologist, USGS/GCMRC
Paul Grams, Research Hydrologist, USGS/GCMRC
Charles Yackulic, Research Statistician, USGS/GCMRC
Graduate Student

Objectives

1. Develop groupings of sandbars based on existing measurements of sandbar response. Grouping sandbars that are functionally similar will allow us to use these groupings to model generalized morphodynamics as part of Objective 2 and document statistically the physical factors most important to different sandbar behaviors for the empirical parametric model in Objective 3.
2. Continue the development and testing of a 3-dimensional large-eddy simulation (LES) model for coupled streamflow, sediment transport, and sandbar morphodynamics (two-way feedbacks between morphology and flow) in eddies.
3. Develop a new parametric (driven by simple/measurable physical parameters) statistical model for sandbar response to high flows and intervening flows over decadal timescales which is based on the existing sandbar monitoring dataset.

Hypotheses/Questions

1. What are the typical sandbar morphologies associated with specific fan, channel, and eddy geometries? Can we develop groupings of bars from a synthesis of existing data sets on sandbar form and dynamics?
2. Are differences in sandbar response driven by the topographic boundary conditions of a given reach, or more strongly linked to flow and sediment supply boundary conditions? To answer this question, can we use a topographically flexible form of the 3-dimensional LES model to assess the dominant controls between sites?
3. What has been the cumulative response of sandbar size (volume and area) to high flow experiments and intervening flows, and how can we parameterize this information statistically or semi-mechanistically to serve as the basis for a predictive model for average or aggregate sandbar responses to future flows? Can we predict the response of individual bars, or groupings of bars that behave similarly, using a comparable modeling approach?

Methods

Objective 1:

In the first phase of our analysis, we will identify groupings of sandbar sites based on morphological character and temporal response to different flow regimes. This will involve using a clustering (dimensionality reduction) approach on metrics such as volume, area, thickness, slope, planform shape metrics, concavity, and grain size, and/or the persistence and time-derivatives of these quantities. Second, we will develop empirical relations between (1) mass balance (erosion or deposition) of the portion of the sandbar above 8,000 ft^3/s and flow/sediment transport parameters, and (2) sandbar mass balance and the morphological characteristics of those bars in deficit, and those in surplus, over specific periods. Third, we will group bars with similar metrics of bar response and bar form based on flow and sediment supply metrics and geometric properties of the channel and eddies using a statistical a statistical analysis of variance (ANOVA) approach to determine the dominant controls that separate the groups.

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

Objective 2:

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

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

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

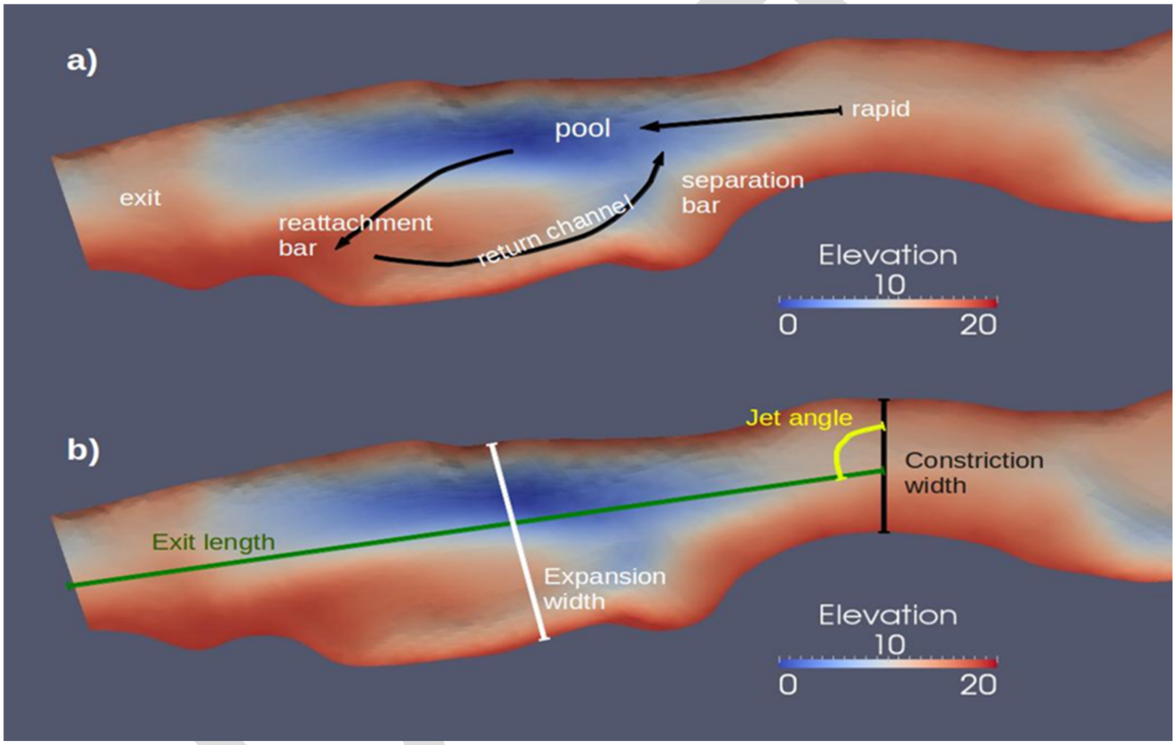

Figure 1. a) General topography of an eddy and b) geometric parameters influencing flow hydraulics.

Objective 3:

We will use existing field and remotely sensed data sets, which include coupled (concurrent and co-located) observations of sandbar response and hydrology, to develop a data-driven model of sandbar response to HFEs and other flow regimes. This model will predict the generalized response of a given sandbar (sandbar volume and/or area) and/or suites of similar bars (Objective 1) given inputs of routinely measured or modeled flow and sediment parameters, and measured or modeled (depending on availability at a given model time step) sandbar parameters. The model will be empirical (as opposed to the mechanistic model of Objective 2), and calibrated and validated with existing long-term sandbar monitoring data. The applicability of the model beyond the monitoring data on which it is built will be evaluated using data from the channel mapping projects (**Project A.2.**), the remote sensing of sandbars (Project **A.1.2.**), the remote camera element of the sandbar monitoring program (Project **A.1.1.**), and the rapid survey project (**A.1.3.**).

Our modeling approach is to begin simply, and incorporate complexity as results from Objectives 1 and 2 allow us to refine our understanding of the key physical processes. First, we will use an empirical statistical approach to model sandbar response for individual bars and for groupings of bars (Objective 1). Our initial approach will use a simple parametric model of individual or grouped sandbar response. Examples include a multiple regression approach, or a model based on statistical unsupervised learning methods that is trained on the existing data set. The latter approach finds parameters based on statistical principles such as minimizing variance, but which have defensible physical meaning. Using results from Objectives 1 and 2, we will attempt to develop a more sophisticated statistical model that is based on calibrated physical parameters derived from physical principles and understanding and empirically-derived response rates. This approach could include re-application of the Wiele and others (2007) approach using the new data sets collected in the last decade if practicable in light of results from the preceding approaches.

For Objectives 1 and 3, we intend to focus initially on Lower Marble Canyon, where there is a higher density of sandbar sites routinely monitored, repeat bathymetric surveys from channel mapping campaigns in 2009 and 2012, and a complete geomorphic base map of channel characteristics and geomorphic units. We will then test the applicability of applying the data-driven empirical model to other reaches in Marble and Grand Canyons. Field measurements combined with Canyon-wide remote sensing data will allow us to document the longitudinal occurrence and persistence of different eddy sandbar types, which may or may not change downstream as a function of canyon morphology and river-level bedrock exposure. This analysis will provide a validation data set to test this approach, as well as insight into improving the approach for longer reaches or in other canyon settings in the CRe.

Outcomes and Products – FY2015

- Presentation at annual reporting meeting on statistically-derived groupings of sandbars (Objective 1) and potential approaches for coupling with LES and statistical modeling (Objectives 2 and 3)
- Development and implementation of "flexible" version of LES model compare with measured sandbar response in different sandbar groupings (Objectives 1 and 2)
- Report/journal article on generalized sandbar groupings from morphological characteristics of the channel and bars

Outcomes and Products – FY2016

- Presentation at annual reporting meeting on results of linking topographically-flexible LES model (Objective 2) with the generalized sandbar groupings (Objective 1)
- Develop a simple statistical, parametric model of sandbar response to HFEs and intervening flows
- Report/journal article on statistical sandbar model to predict sandbar response using the monitoring data set and/or results from the "flexible" LES model

Outcomes and Products – FY2017

- Presentation at annual reporting meeting integrating the statistical and LES modeling approaches to understand spatial and temporal variations in sandbar dynamics
- Continue refining the parametric model, with the potential for developing a semi-mechanistic model incorporating results from Objectives 1 and 2
- Report/journal article on coupled flow and morphodynamic LES model of Grand Canyon sandbars

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

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

Objectives

1. Carry out repeat high-resolution bathymetric and flow-field surveys over sand bedform fields in select reaches, over a range of discharges, including a controlled flood (Wright and Kaplinski, 2011) and flows associated with routine dam operations.
2. Use this data to estimate bedload and bed material sand fluxes associated with the deformation and migration of bedforms by applying, and modifying where necessary, existing numerical techniques and theory.
3. Determine a bedload 'rating curve' which relates sand flux as bedload with routinely measured flow and sediment quantities (discharge, or suspended sand flux, or both).
4. Use the rating curve in conjunction with a discharge model to estimate a total bed-material sand mass balance for Marble Canyon and eastern Grand Canyon (stations at RM 30, RM 61, and RM 87), combining estimates of sand bedload flux with sand suspended flux to enable estimation of total sand transport.
5. Develop a conceptual 'bed state indicator' model relating bedforms in a given reach classified by their morphology and sedimentology to the surplus or otherwise of sand in the bed, and therefore the propensity of the bed in that reach to contribute sand for sandbar building during controlled floods.
6. Examine the two-way feedbacks between evolving bedform fields and spatial distributions of flow and sediment concentrations, in order to better understand the potential time-varying importance of bedload sand flux to estimate the representativeness of suspended sediment measurements for bed material flux at discrete locations.

Questions / Hypotheses

1. What is the contribution of bedload to time-integrated sand flux in the Colorado River in Grand Canyon? How does this vary with discharge, suspended sand load, hydraulic geometry, and bed sediment grain size? We hypothesize that the fraction of sand moving as bedload varies inversely with discharge above the suspension threshold, positively with bend radius and channel width, and positively with grain size.
2. Does bedload flux scale with suspended sand flux? We hypothesize that 1) bedload sand flux varies non-linearly with suspended sand flux, and 2) the importance of incorrectly estimating bedload sand flux increases at low discharges and transport stages.
3. Can reach-scale estimates of sand flux and sediment mass balance improve with direct quantification of the contribution of bedload transport, using routinely measured quantities at gaging sites (discharge, suspended sediment concentration and grain size) for inclusion in operational sand flux models? We hypothesize that more robust parameterization of bedload flux will enable us to partially if not completely account for discrepancies between morphologic and suspended sediment based estimates of sand mass balance.
4. Can geometric and sedimentologic characters of bedforms be used as a 'bed state' indicator? What bedforms (if any) indicate sediment-starved beds, and what (if any) represent significant stores of sand which could be re-mobilized during controlled floods to build sandbars? We hypothesize that certain bedforms shapes and grain sizes are indicative of thin veneers of sand, and others indicate thick sand bed deposits. The use of bedform classification (geometric characteristics and sedimentology) is common in field and experimental settings to indicate the presence or otherwise of a starved sand bed. For example, the existence of 'sand stripes' indicate relatively starved bed conditions (Grams and Wilcock, 2007), as do dunes with coarse underlying material exposed in the troughs. High amplitude dunes with more regular geometries indicate areas with a surplus of sand-sized sediment.
5. Do evolving bedform fields alter hydraulic conditions and suspended sediment concentrations? We hypothesize that, for a given flow field and upstream suspended sediment supply, an evolving bedform field alters the spatial distribution of shear stress sufficiently to alter the concentration and spatial distribution of suspended sand. This is manifest as non-equilibrium responses in the distribution of sand flux between bedload suspended load.

Methods

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

In year 1, we propose to conduct this work in the water and sediment gaging pool at RM61, above the confluence with the Little Colorado River and within Natal Origins Reach 4. In order to maximize the efficiency of the fieldwork, and minimize costs, this in conjunction with a Natal Origins field trip. This site has been mapped using multibeam bathymetry in May 2009, May 2012, and August 2013. A well-developed bedform field is present (Figure X). We propose to map the same bedform fields repeatedly as many times as possible over a week, in conjunction with ADCP measurements along multiple transects (Figure X), which have been shown to adequately characterize the near-bed velocity flow field responsible for mobilizing and transporting sediment as bedload under varying discharges. This intensive repeat mapping and sampling of an entire ~1 mile reach, near an existing long-term gauging site, and over multiple days with a range of flows, is the best strategy for compiling enough data to answer the suite of scientific questions posed above. Bedload and bed material fluxes will be estimated by applying to the MBES-derived data a suite of existing techniques, principally the migration of bedforms (Simons et al., 1965; Duffy and Hughes-Clarke, 2005) and time-varying vertical exchanges with the suspended load (McElroy and Mohrig, 2009).

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

We also propose to collect full water-column imaging from MBES at discrete locations above dunes in conjunction with both physical samples of suspended sediment and the 15-minute acoustic suspended sediment time-series at the gauging station at RM61. This opens the door to calibrating MBES acoustic backscatter for suspended sediment concentration, thus creating making possible a mapping 3D time-integrated field (spatially static) of suspended sediment, using the methods detailed in Simmons and others, (2010). Such information is a requirement of objective 6 and enables us to answer questions related to the interaction of an evolving bedform field with a spatially non-uniform flow and sediment field, and the representativeness of suspended sediment measurements at discrete locations.

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

We anticipate at least two major scientific products and at least one major management product. In addition yearly reports and presentations at national-scale conferences will be produced. One scientific manuscript will deal exclusively with bed load fluxes through the Grand

Canyon and its physical controlling factors. The second will focus on the relations between bed load and suspended load, and it will include a treatment of Grand Canyon sediment budgets including bedload. Finally, we will produce a document that makes recommendations for if and how to further incorporate bedload with sediment monitoring in the canyon.

Outcomes and Products – FY2015

- Presentation on project progress at annual reporting meeting.

Outcomes and Products – FY2016

- Presentation at annual reporting meeting.
- Journal article on measurements of bedform migration and physical controls on bedload sediment transport.

Outcomes and Products – FY2017

- Presentation at annual reporting meeting.
- Journal article on relation between bedload and suspended sediment load in the Colorado River.
- Report/Journal article on procedures for measuring and estimating bedload.

Project Element 3.5. Control Network and Survey Support

Keith Kohl, Surveyor, USGS/GCMRC

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

The control network is the set of monumented and documented reference points (benchmarks) that exist along the river corridor and on the rim together with the collection of observations that determine the relative and absolute positions of those points. Those points serve as the basis for referencing all ground- and air-based monitoring observations. Currently, the control network includes more than 7,000 GPS observations and more than 2,000 optical observations that determine the precise location of 1,303 benchmarks in the river corridor and on the canyon rim. This project includes work in three broad categories: (1) building the control network, (2) direct support of research and monitoring activities, and (3) storage and archival of the control database.

Building the Control Network

The primary task of building the control network involves making GPS observations at new and existing benchmarks. This effort is nearing completion, and most segments of the river corridor now have a sufficient number of control points to support monitoring activities.

Building the control network also requires addressing the difference that exists between ellipsoid height, which is provided by the GPS observations that GCMRC makes, and orthometric elevation (i.e. NAVD88), which can be obtained only by gravity measurements or precise leveling. The deviation between ellipsoid height and orthometric height can be as large as 10 cm over a distance of 1 km. This problem exists everywhere and is a major focus of work by the National Geodetic Survey (NGS). The problem has not been resolved in Marble and Grand Canyons because of the remote location, low population, and difficult access. We have made progress on this problem by incorporating existing leveling measurements into the control network. We are also encouraging the NGS to conduct a campaign of gravity measurements for the Grand Canyon region.

Support of Research and Monitoring Projects

The two major projects that require survey support in 2015-2017 are the sandbar (**A.1.**) and sediment storage (**A.2.**) project elements and Project J. The sandbar and sediment storage project elements described here utilize the control network, and the expertise of the survey staff in data collection efforts. Geodetic control work supports the remote sensing data collection effort by panel placement and recovery, collecting reference base station data for overflights, and processing the data to publish GNSS results for the stations within the NGS database. Other projects that receive survey support include the Streamflow, Water Quality, and Sediment Transport project (Project B), and the Vegetation Monitoring project (Project I).

Storage, Archival, and Documentation of the Control Network Database

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

This project will result in updates to the National Geodetic Survey Integrated Database (NGSIDB) of all available Height Modernization and Benchmark stations.

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

A. Investigators

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Helen Fairley, Research Specialist, USGS, Grand Canyon Monitoring and Research Center
Joshua Caster, Geographer, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

The connectivity between fluvial, aeolian and hillslope processes in the context of river management is important and has implications for the effects of dam operations on archaeological sites and other cultural and natural resources within the Colorado River ecosystem (CRe). In particular, quantifying the relative importance and interactions of river-related factors, riparian zone characteristics, and other phenomenon such as weather, that might individually and collectively influence connectivity can provide insight into the influence of dam operations on the condition of archaeological sites. This proposal is composed of two integrated elements that collectively comprise a single research and monitoring project. The elements are: 1) a landscape scale analysis of the connectivity between fluvial processes and patterns at lower elevations (below the 45,000 ft^3/s stage) and geomorphic processes and patterns at higher elevations (above the 45,000 ft^3/s stage); and 2) implementation of a long-term monitoring component to evaluate if and how much the hypothesized interactions between fluvial and hillslope processes affect the condition of cultural resource sites in the Colorado River corridor.

C. Proposed Work

C.1. Project Elements

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

Joel Sankey, Research Geologist, GCRMC/USGS
Amy Draut East, Research Geologist, PCMSC/USGS
Helen Fairley, Research Specialist, GCMRC/USGS
Joshua Caster, Geographer, GCMRC/USGS

The primary objective of element 4.1. is to explain how connectivity along the fluvial-aeolian-hillslope continuum varies spatially throughout the river corridor; and temporally, particularly in the recent decades of restricted power plant operation with controlled floods. We define connectivity (Merriam, 1984) as the “degree to which a landscape facilitates or impedes movement among resource patches” (Taylor and others, 1993). This project element includes three sub-elements that examine connectivity by focusing on the potential for movement of sand resources by aeolian geomorphic processes between patches of modern fluvial sand sources (e.g., sandbars) and generally higher elevation modern-fluvial-sourced (MFS) sandscapes. In the context of landscape connectivity, vegetation and topography can be important controlling factors that decrease the length of the connected pathway between source (e.g. sandbar) and sink (MFS sandscape) which reduces the potential for movement of sand resources (Okin and others, 2009). The project elements are designed to examine connectivity and potentially important controlling factors at different spatial and temporal scales as well as geographic location and extent. The first sub-element will examine landscape-scale spatial variability using a combination of remote sensing and GIS analyses of existing digital imagery and topography data to test hypotheses developed during the FY 13/14 work-cycle about what environmental factors related to river operations control the location and magnitude of aeolian sand deposits that contribute to the stability of archaeological sites. Sub-element 1.2 will extend the first analysis farther back in time by conducting visual interpretation of historical oblique photos to assess whether hypothesized changes due to dam operations are supported by photographic evidence. Sub-element 1.3 will investigate how the processes and controls that govern connectivity are impacted by the effects of river regulation on sediment supply. This last sub-element will contrast observations of aeolian sand distribution in Grand Canyon with other, analogous river systems, specifically Desolation and Gray Canyons of the Green River. The sub-elements are each described in further detail below in this subsection.

In sub-element 4.1., we will conduct landscape-scale, remote sensing and GIS analyses of existing digital imagery and topography as well as geospatial databases developed and previously reported on for work conducted in the FY 13/14 work plan (Sankey and Draut, in review; Draut East,2014). We will spatially analyze the relative importance of the hypothesized controls independently for each date of "corridor-wide" digital imagery and topography that we have (e.g., 2002, 2009, and 2013). Methodological steps will be to first expand the aeolian sand map completed for the FY 13/14 work plan to include the greater river corridor using image classification techniques and the existing maps as training data to identify river-derived upland sand (above 45,000 ft^3/s) that is active or inactive with respect to aeolian transport. We will next quantify relationships of the spatial proximity of aeolian sand units and their areal dimensions to the location and dimensions of adjacent and upwind fluvial sand (sandbar) deposits. We will similarly quantify relationships of aeolian sand units to alternative sediment sources that are adjacent and upwind, including exposed terrace scarps, tributary mouths, and open campsite areas. Work completed in the FY 13/14 work plan described the role, in many locations, of riparian vegetation that produces a barrier to the inland and upslope transport of fluvially-sourced aeolian sand (Draut East,2014). Previous work also quantified the long-term trends of: (1) riparian vegetation that has consistently increased at lower elevations and encroached towards increasingly lower stage-elevations in response to decreased flood magnitude and duration post-dam; (2) xeric (upland) vegetation that has exhibited increases and decreases at higher stage-elevations in response to regional climate and specifically episodes of drought (Sankey and others, in preparation). Therefore, an important step will also be to examine how the presence, dimensions, and long-term stability of vegetation located between aeolian sand units and fluvial sand (sandbar) deposits, or formerly open sand areas that may have served as source areas for aeolian landscapes, are related to the distribution and size of contemporary mapped aeolian sand units. Finally, we will quantify temporal changes in area and dimensions of aeolian sand units and attempt to explain changes as a function of variability in fluvial sand sources, alternative sediment sources, and transport barriers. We will conduct the change analysis for the approximately decade time period of 2002 to 2013 for which high resolution digital imagery are available. We propose to statistically test the independent and interacting effects of the hypothesized explanatory variables for the response of aeolian sand unit area and change. Statistical tests could employ mixed model analysis with hypothetical effects (predictor variables) that could include, for example: distance and direction to fluvial sand; area of fluvial sand; distance, direction to, and area of vegetation barrier; stage-elevation of aeolian sand; relief or elevation difference between aeolian and fluvial sand; distance and direction to alternative sediment sources or topographic barriers such as camp sites or tributary channels, respectively; inferred or measured wind direction; as well as additional and potentially random effects such as geomorphic reach or distance from Glen Canyon Dam. The work in sub-element 1.1 will be led by Joel Sankey with collaboration from Amy Draut East and Joshua Caster.

In sub-element 1.2., we will extend the analysis back farther in time, to ascertain the degree to which environmental conditions at or near cultural sites have changed during the past > 50 years by comparing conditions in areas that appear to have functioned differently as aeolian landscapes in the past compared to current conditions. This work will be completed using qualitative visual comparisons of historical oblique imagery and current surface conditions (e.g., visual evaluations of more or less soil crust, vegetation cover, etc.). Samples of cultural sites and aeolian sand areas will be selected that were captured in oblique imagery collected by Stanton (1890), Birdseye (1923), Schwartz (1965), Euler (1960s), Shoemaker (1969), and Webb and others (1990, 2010). Photos will be examined and qualitatively assessed in terms of whether the historical imagery shows more or less biologic crust cover and vegetation cover within specific areas designated as cultural sites and also within the areas that appear to have served as aeolian source areas to cultural sites. The current state of these cultural sites and aeolian sand areas will be similarly assessed based on the more recent site photos as well as recent site descriptions (e.g., from site investigation work completed in 2013 and 2014). An important outcome of this analysis will be an estimate of proportion of cultural sites for which the potential influence of aeolian sand inputs has changed with time, relative to changes in environmental characteristics including vegetation and biologic crusts. The work in sub-element 1.2 will be led by Helen Fairley with collaboration from Joel Sankey, Amy Draut East, and Joshua Caster.

In sub-element 1.3, we will investigate how the processes and controls that govern connectivity are impacted by the different effects of river regulation on sediment supply. This work will contrast observations in Grand Canyon with those in Desolation and Gray Canyons of the Green River, Utah. There, previous mapping has shown that several large aeolian deposits exist (Elliott, 2002) that are likely sourced from fluvial sandbars. In that system with greater fluvial sand supply and a flow regime that more closely resembles natural flows (i.e., upstream dams there affect flow and sediment supply much less than does Glen Canyon Dam in Marble-Grand Canyon), we aim to map active and inactive sand deposits to test the hypothesis that the proportion of active aeolian sand area there will be greater than in Marble-Grand Canyon. This will also complement comparative work done in the Colorado River corridor through Cataract Canyon (Draut, 2012), but using a canyon where aeolian dunes are a more common feature of upland river-corridor morphology. The work in sub-element 1.3 will be led by Amy Draut East, conducted by an M.S. student at Utah State University supervised by J.C. Schmidt, with collaboration from Joel Sankey.

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

Joel Sankey, Research Geologist, GCRMC/USGS
Amy Draut East, Research Geologist, PCMSC/USGS
Helen Fairley, Research Specialist, GCMRC/USGS
Joshua Caster, Geographer, GCMRC/USGS

The primary objective of element 4.2. is to use monitoring to evaluate whether the archaeological site classification developed and applied in 2013 and 2014 (Draut East,2014) provides useful, site-specific expectations of landscape response to dam operations and high flow events. In proposing this work we have considered the recent synthesis of 5 years of monitoring surface-elevation changes at archaeological sites in Grand Canyon (Collins and others, in review a) in the context of the site classification system (Figure 1 in Scientific Background section of this proposal). Figure 1 shows the mean response with time of runoff and aeolian surface change for different classes of archaeological sites measured with lidar during site investigations between 2006 and 2010. The large uncertainties (shown by bars that are the standard error of the mean for n sites in Figure 1) demonstrate the inherent limitations associated with the small sample sizes (# of sites per class). Therefore, while the existing data provide useful information about landscape response to dam operations and high flow events, additional data (i.e., additional sites but also additional repeat visits of previously measured sites) are required to tighten the uncertainty about the mean responses and identify any observed differences that are statistically significant.

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

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

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

We propose to continue monitoring at comparable time intervals to those demonstrated by Collins and others (in review a) to be useful for relating surface elevation changes to meteorological events (Table 1). We propose to use site-specific monitoring of surface elevation change with terrestrial lidar to evaluate whether the aeolian sand classification developed and applied in 2013 and 2014 (Draut East,2014) provides useful, site-specific expectations of landscape response to dam operations and high flow events. We will incorporate additional sites to the set measured by Collins and others (in review a) and in surveys completed in 2013 and 2014, such that we maintain a meaningful number of sites (i.e., n = 4 clearly presents limitations for evaluating the central tendency and uncertainty among classes of sites; even a slightly larger sample size might be extremely useful for identifying the variety of landscape process trends) of each of the classification types 1, 2(a+b), 3 and 4. Specifically, in 2016 and 2017 we anticipate making measurements at additional type 1 and 2 sites (e.g., ~ 1-3 sites per class that were not measured previously). We would also revisit several of the previously, though less frequently measured sites of each class type (e.g., 1-2 per class). With the combination of the existing and new terrestrial lidar survey time series data we will test the hypotheses of whether:

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

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

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

Terrestrial Lidar Scanners (TLS) have proven to be a useful and efficient tool for tracking fine-scale changes of upland environments associated with cultural sites in Glen, Marble and Grand Canyons, and the technology also holds promise for future interdisciplinary physical science and aquatic ecology work at GCMRC focused on terrestrial settings and near-shore environments. Although in past years GCMRC has relied on personnel and equipment from other USGS centers to perform TLS surveys, for this project, we intend to rely on "in-house" terrestrial lidar capacity at GCMRC. This will require the purchase of a TLS scanner and hiring of a survey/scanner technician in year 1. River trips in year 2 and year 3 will be conducted to collect lidar topography using protocols developed and tested in the FY 13/14 and prior GCMRC work plans. Pending NPS approval, the currently deployed automated weather stations and stationary cameras (installed in FY13) could continue to collect data on local weather conditions at 24.5 mile, 70 mile, 126 mile, and 223 mile (all type 1 sites in the recent classification) to refine our current understanding of how local weather events contribute to the erosion and/or deposition measured at this sample of type 1 sites; these data are useful for attributing site-specific surface elevation changes to meteorological events. The weather stations that are currently deployed in GRCA are permitted to collect data through April 30, 2015, and we will discuss with the NPS extension of the permit through the duration of this project (December, 2017).

Project 5. Foodbase Monitoring and Research

5.1 Are Aquatic Insect Diversity and Production Recruitment Limited?

A. Investigators

Theodore Kennedy, Research Aquatic Ecologist, USGS, Grand Canyon Monitoring and Research Center
Jeffrey Muehlbauer, Research Ecologist, USGS, Grand Canyon Monitoring and Research Center
Charles Yackulic, Research Statistician, USGS, Grand Canyon Monitoring and Research Center
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
David Lytle, Associate Professor, Oregon State University

B. Project Summary

The absence of mayflies, stoneflies, and caddisflies (i.e., EPT) from the Colorado River in Glen Canyon, and the rarity of these insect groups in Marble and Grand Canyon, indicates this segment of river is unhealthy. The stressors that prevent mayflies, stoneflies, and caddisflies (i.e., EPT) from re-colonizing the Colorado River may also be contributing to low overall production of midges and blackflies (i.e., the foodbase that supports key fish populations). We present 5 hypotheses that explain how specific environmental stressors (i.e., 2 temperature hypotheses, 1 dispersal hypothesis, and 2 flow hypotheses) may be constraining the diversity and productivity of aquatic insects downstream of Glen Canyon Dam. We then outline 8 Project Elements that will collectively evaluate the validity of the hypothesis that we believe is the most plausible (i.e., *EPT taxa are recruitment limited, because hydropeaking causes high egg mortality*). Specifically, we propose: 1) continued citizen science emergence monitoring in Marble and Grand Canyon to describe insect population response to ongoing adaptive management experimentation; 2) conducting field studies of emergence, egg-laying, and egg-mortality to directly evaluate the validity of two assumptions that are implicit in this flow related hypotheses; 3) conduct a synthesis of stressors and controls on EPT distributions globally to further evaluate the validity of the hypothesis; 4) conduct a comprehensive synthesis of the aquatic foodbase in western US tailwaters; 5) observational studies of midge and blackfly egg-laying in Grand Canyon to identify whether hydropeaking is also leading to recruitment limitation of their populations; 6) laboratory studies on egg-laying and egg-mortality that describe the desiccation time and temperatures at which 50% (a clinical threshold for mortality) of midge or blackfly eggs become non-viable; 7) insect emergence studies in Upper Basin segments via citizen science light trapping, which will provide context for, and aid interpretation of, the spatial and temporal patterns evident in Grand Canyon emergence data; 8) observational studies of egg-laying for EPT taxa via studies in the Upper Basin. We also propose a novel flow experiment for testing the validity of the focal hypothesis that involves stable flows every weekend from May through August.

C. Proposed Work

We presented five hypotheses that explain how specific environmental stressors may be constraining the diversity and productivity of aquatic insects downstream of Glen Canyon Dam. As a first step toward framing the problem, we focused on the role that individual stressors may be playing in driving observed patterns of insect diversity and productivity, even though there are likely significant interactions among stressors (e.g., between temperature and flow; Olden and Naiman 2010). We also chose not to present hypotheses that involve interactions among stressors, because managers presently have limited ability to actively mitigate some of the stressors we identified. For example, the high-cost (>$150M) and risks (i.e., invasion by warm-water nonnatives) associated with installation and use of a selective withdrawal structure on Glen Canyon Dam mean active temperature mitigation is unlikely (i.e., **H1** and **H2**). Mitigating and testing the dispersal limitation hypothesis (**H3**) could be accomplished through translocations of insects from other river segments, but, in our opinion, this hypothesis requires too many unreasonable assumptions, none of which are actually testable, to warrant serious consideration at this time. In contrast, mitigating the negative effects of hydropeaking under both **H4** and **H5** is logistically possible. However, the diversity assumption implicit in **H4** (i.e., EPT are much more susceptible to catastrophic drift than midges and blackflies) seems unreasonable, and would be difficult to test. Project 5.2 (Patterns and controls of invertebrate drift in Colorado River tailwaters) describes research and monitoring that will address uncertainties relative to **H4**. Due to the difficulties in testing the low diversity tenets of **H4**, that proposal focuses more specifically on the environmental factors controlling drift.

The two assumptions that are implicit in **H5** both seem reasonable (i.e., substantial egg-laying occurs near shorelines, and mortality of eggs subjected to drying is high), and both assumptions can be tested with field and laboratory studies. We focus exclusively on testing **H5** in the remainder of this Project description, because emergence and egg-laying of aquatic insects are very poorly studied processes, particularly in the context of river regulation and hydropeaking. Most importantly, mitigating potentially negative effects of recruitment limitation, assuming **H5** is true, has the highest probability of leading to a large and positive increase in insect diversity and productivity, even as other stressors persist.

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

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

We propose a novel experimental design for testing the validity of **H5** that involves stable flows every weekend from May through August (34 days total). The discharge on weekends would be the minimum discharge for that month, which will ensure that the insect eggs laid during weekends will never be subjected to drying due to lower water levels at any point prior to larval development. No change in monthly volumes, ramping rates, or the daily range during weekdays would be required as part of this experiment. To offset the smaller water releases that would occur during weekends within a given month, larger releases would need to occur during the weekdays within a given month.

The timing of the proposed experiment is informed by citizen science light trapping results demonstrating that midges, and to a lesser extent blackflies and micro-caddisflies (Order Trichoptera, Family Hydroptilidae), are emerging from the mainstem throughout this period (Kennedy unpublished data). Because this experiment will provide an ideal egg-laying environment (i.e., stable shorelines) at regular intervals throughout the emergence and egg-laying season, it should elicit both short-term (i.e., month-to-month) and long-term, (i.e., year-to-year), population-level responses from aquatic insects if **H5** is true.

C.1. Project Elements

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

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

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Charles Yackulic, Research Statistician, USGS/GCMRC

The citizen science sampling of insect emergence initiated by Kennedy in 2012 has yielded an unprecedented dataset of spatial and temporal patterns in aquatic insect emergence throughout 225 miles of Grand Canyon. These data are also beginning to shed light on how flow management affects the critical adult life stage of aquatic insects. This project has also become a powerful outreach tool for communicating Grand Canyon science, and the important role that adaptive management plays, to dozens of river guides and thousands of passengers annually. In many ways, this dataset has been the basis for the research and questions described in this proposal, and we propose to continue this citizen science monitoring in FY 2015-2017. In addition, if flow management changes aimed at increasing insect productivity and diversity in the Colorado River are initiated, data from this monitoring program will be essential in tracking any changes to aquatic insect populations.

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

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

The main focus of this project element is addressing the two assumptions that are implicit in **H5**. Specifically, this project will quantify 1) the proportion of egg-laying by aquatic insects that occurs in the varial zone relative to permanently inundated habitats, and 2) rates of mortality for eggs that are subjected to daily drying. Field studies of egg-laying will be conducted at sites where the varial zone is wide vs. narrow, and sites where daily flow minima occur during daytime hours vs. nighttime hours. Field studies on egg mortality will be complemented by more controlled laboratory studies on egg mortality (see Task 6).

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

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

All the hypotheses described above are predicated on an understanding of the stressors and controls that affect the ability of insects to colonize, reproduce, and persist in aquatic ecosystems. The hypotheses we presented are based on sound science for aquatic insects in general; however, in moving toward potential mitigation strategies that will promote colonization or increased production of target species, a better understanding of species-specific traits and stressors will be required (see Table).

Life Trait	Midges (Chironominae, Orthocladiinae)	Blackflies (*Simulium arcticum* complex)	Ephemeroptera (mayflies) *Baetis*	Plecoptera (stoneflies) *Hydroperla*	Trichoptera (caddisflies) *Hydropsyche*
Feeding mode	Collector-Gatherer	Filter feeder	Collector-gatherer	Leaf shredder, then predator	Filter feeder
Generations per year	Multiple	One or multiple	Multiple	One	One
Egg-laying location	Water surface	Below water line on vegetation	Shallow riffles, under stones	Head of riffles	Submerged object
Pre-egg laying	1-2 days	Variable, requires blood meal	1 day	2-5 days	A few days
Fecundity (eggs per female)	1000-2000	300-600, often large clumps from multiple females	~1000	150-300 per egg mass (1-3 masses each)	300-500
Egg incubation	Days to weeks	Days to weeks	Weeks	Weeks-months	Days-weeks
Notes	Eggs masses often float	Overwinters as diapausing egg	Hatching period highly variable	Synchronous hatching	

Table of Life History Information for Select Aquatic Insect Taxa. Information on midges and blackflies is specific to the sub-families (midges) or species (blackflies) that are present and widely distributed in the Colorado River. Life history information for representative genera from Ephemeroptera, Plecoptera, and Trichoptera are also presented, even though these taxa are not present in the Colorado River in Grand Canyon. This type of species-specific information will inform the development of field studies and provide insights into invertebrate population responses to the flow experiment we have proposed. From: Merritt and Cummins, 1996, An Introduction to the Aquatic Insects of North America.

Project Element 5.1.5. Natural history of oviposition for species present in Grand Canyon

Theodore Kennedy, Research Aquatic Ecologist, Grand Canyon Monitoring and Research Center
Eric Kortenhoeven, Ecologist, USGS/GCMRC
Anya Metcalfe, Ecologist, USGS/GCMRC

To understand how environmental stressors affect the populations of aquatic insects present in Grand Canyon, a better understanding of their life history is required. For instance, additional, observational information on the oviposition (egg-laying) behavior of black flies and midges in the Colorado River in Grand Canyon will help support or discredit the hypotheses listed above, and will inform the extent to which alterations to flow management may increase production of the aquatic food base.

Project Element 5.1.6. Laboratory studies on insect oviposition and egg mortality associated with changing water levels

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Adam Copp, Ecologist, USGS/GCMRC

Many of the hypotheses listed above are based on mortality at key insect life stages, particularly the effect of desiccation on egg-mortality (**H5**). Lab or experimental mesocosm studies are highly amenable to isolating such effects and providing conclusive data on the impact of individual stressors, such as the desiccation time and temperature at which 50% (a clinical threshold for mortality) of midge or blackfly eggs become non-viable.

Project Element 5.1.7. Comparative emergence studies in Upper Basin using citizen science light trapping
Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC

Citizen science emergence monitoring in Grand Canyon (Project Element 1) will provide information on insect population response to Glen Canyon Dam operations; however, it is difficult to put the temporal and spatial patterns present in these data into context without comparable data from other regulated and unregulated rivers that have different characteristic flow regimes. Thus, we propose to carry out similar studies in Upper Basin tailwaters including Flaming Gorge Dam, Fontenelle Dam, and Navajo Dam. We will also collaborate with citizen scientists to quantify insect emergence in segments that are unregulated, such as the Green River in Desolation-Gray Canyon, the Colorado River in Westwater and Black Rocks, and Cataract Canyon. These data will elucidate the degree to which unique operations of Glen Canyon Dam affect insect behaviors and life stages, and the degree to which certain behaviors and population dynamics are consistent across segments of the Colorado River Basin. Note that the three years of citizen science emergence monitoring that we have acquired from Grand Canyon (2012-2014) will provide an experimental 'control' in the event the flow experiment we propose is implemented. Citizen science monitoring in the San Juan River was already initiated in April 2014 in collaboration with Grand Canyon Youth, and will occur through FY 2014 and, ideally, into future years as well. As with the Grand Canyon citizen science monitoring, we expect this collaboration to also provide a large outreach benefit to the GCDAMP.

Project Element 5.1.8. Natural history of oviposition for EPT via studies in the Upper Basin

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC

As described in Task 5, understanding the life history behaviors of aquatic insects will provide useful information for predicting insect population responses to flow management. For midge and blackfly species, these studies can be done in Grand Canyon. However, for target EPT taxa that are not currently present in Grand Canyon, their life histories must be studied in river systems where they are extant. The closest segments where these species are present is the Upper Colorado River Basin, specifically tailwaters such as those downstream of Flaming Gorge, Fontenelle, and Navajo Dams, and the unregulated Cataract Canyon reach that serves as a proxy for conditions in the pre-dam river. Thus, we propose natural history studies similar to those in Task 5, to be carried out in these Upper Basin segments with a focus on EPT taxa.

5.2 Patterns and controls of aquatic invertebrate drift in Colorado River tailwaters

A. Investigators

Jeffrey Muehlbauer, Research Aquatic Ecologist, US Geological Survey, Grand Canyon Monitoring and Research Center

Theodore Kennedy, Research Ecologist, US Geological Survey, Grand Canyon Monitoring and Research Center
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center
Scott Wright, Research Hydrologist, USGS, California Water Science Center

B. Project Summary

Invertebrate drift is a ubiquitous phenomenon in freshwaters, in which aquatic insects and other macroinvertebrates leave the channel bed and become entrained or caught in the water column. Understanding invertebrate drift concentrations and the spatial and temporal variation in drift is critical from a fisheries perspective, because these drifting invertebrates represent a key food resource for many fish species. Relevant to the Colorado River, the endangered humpback chub (Gila cypha) and recreationally-important non-native rainbow trout (Oncorhynchus mykiss) are both classified as “drift-feeding fishes,” meaning that they rely on invertebrate drift as the key component of their foodbase.

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

In this project, we outline 5 tasks related to characterizing and monitoring invertebrate drift in the Colorado River, and well as the hydrological and geomorphic conditions that initiate this drift. Most of this work is based in Glen, Marble, and Grand Canyons; however, additional work will also be done in Upper and Lower Colorado River Basin tailwaters. Together, these research projects will greatly improve our understanding of where, when, and how invertebrate drift occurs in the Colorado River. Critically, these studies will elucidate if drift conditions and the state of the foodbase downstream of Glen Canyon Dam are unique or, conversely, the degree to which they are more broadly ensconced within the range of drift conditions found in other Colorado River tailwaters.

C. Proposed Work

C.1. Project Elements

Project Element 5.2.1. Continue characterizing and monitoring drift and insect emergence in Glen Canyon

Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC

Monthly invertebrate drift measurements have been taken longitudinally at 6 stations throughout Glen Canyon (RM -11, -8, -4.9, -3.5, -2.1, 0.2) and laterally at a cross section at Lees Ferry (RM 0) since January 2013. Monthly monitoring of emergent insects using sticky and light trap sampling was also initiated throughout Glen Canyon in January 2014. This monitoring is carried out using published methods developed by our lab group (Kennedy and others, 2013a; Kennedy and others, 2014; Smith and others, 2014; see Appendix, below). These monitoring efforts will be used to describe spatial and temporal patterns of drift throughout Glen Canyon and will be compared to similar data we will collect from other tailwaters as outlined in Project Elements 2 and 5, below. In addition, the emergent insect monitoring in Glen Canyon will be linked to the citizen science emergent insect study initiated in 2012 (Kennedy and others, 2013a; see Appendix, below) to provide an unprecedented longitudinal dataset of emergence, from Glen Canyon Dam at RM -16, to Diamond Creek 225 miles downstream. Extending insect emergence monitoring into Glen Canyon will allow us to better identify the role that flow management plays in driving insect population dynamics, because Glen Canyon is unaffected by sediment turbidity. Emergent insect monitoring will also be coupled with the drift data to describe the proportional relationship between concentrations of drifting invertebrates (i.e., food for fishes) and emergent insects (Statzner and others, 1986; Statzner and Resh, 1993) in the Colorado River. Emergent insects are more easily sampled than drift, and better quantifying the nature of this relationship in Glen Canyon and at the Natal Origins sites in Marble and Grand Canyon (as outlined in Project Element 2, below) will allow the citizen science emergent insect database to be used as a proxy for drift concentrations throughout the Colorado River.

Project Element 5.2.2. Continue Natal Origins drift monitoring in Glen, Marble, and Grand Canyon

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC

Invertebrate drift has been monitored as part of the ongoing fish Natal Origins (NO) project since 2012. Drift samples are taken at all NO sites (RM -3.5, 18.9, 39.5, 60.15, 63.7) and during the run-out of NO trips at RM 63.7, 71.2, 88, 138.6, 166, and 225. Drift data from NO sites will eventually be linked to fish diet, abundance and distribution data collected concurrently with NO quarterly sampling (see Project ? in work plan). NO drift data will also be used to parameterize rainbow trout bioenergetics models for Glen, Marble, and Grand Canyon (Project H). High resolution drift monitoring will also be used to build a coarse-scale map of drift patterns throughout the Colorado River, as outlined in Project Elements 3 and 4, below.

In FY 2013-2014, 20 drift samples were taken quarterly at each NO site (100 total samples per trip, or 500 per year). In this work plan, sampling effort per site visit will be reduced by ~50% (10 samples per site) to reduce laboratory sample processing burdens. Power analysis indicates this reduction will only marginally affect our ability to draw inferences from the data. Intensive diet sampling was also conducted at each NO site during FY 2012-2014, resulting in 100 samples for rainbow trout gut content analysis per trip, or 400 per year. This diet analysis sampling will be discontinued in this work plan, because the three years of intensive diet sampling are sufficient to describe the relationship between drift concentrations, water clarity, and rainbow trout feeding habits. During the last two years of the NO project (i.e., FY 2015-2016), we will predict rainbow trout feeding habits based on drift concentrations and water clarity, rather than continuing with time-intensive fish gut content analysis.

Project Element 5.2.3. Link drift at Natal Origins project transects to channel bed shear stress

Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC
Scott Wright, Research Hydrologist, USGS, California Water Science Center

Bed shear stress conditions will be quantified at all drift sites sampled during NO trips (11 total sites). This work can be done over the course of one NO trip using an acoustic Doppler current profiler (ADCP) with standardized methods developed previously in Glen Canyon (Muehlbauer and others, 2013). These hydrodynamic data will also be useful in fish bioenergetics modeling at the NO sites, and in understanding spatial variability in habitat conditions affecting both invertebrate and fish distributions. Further, these data will be used to characterize the functional relationship between physical environmental controls and invertebrate drift at a coarse scale throughout Glen, Marble, and Grand Canyon, as outlined in Project Element 4, below.

Project Element 5.2.4. Link invertebrate drift patterns to substrate conditions in Glen, Marble, and Grand Canyon

Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC
Scott Wright, Research Hydrologist, USGS, California Water Science Center

This task will integrate spatially and temporally-extensive data on aquatic macroinvertebrate drift, bed shear stress, and sediment grain size distributions. Much of the data collection required has already been completed or is ongoing. The critical work remaining for this task is to systematically link available point data on drift and bed shear stress to channel bed grain size estimates at these same locations. Such data can be used to predict the shear stress conditions under which incipient motion of bed sediment will occur for a given substrate habitat patch (Shields, 1936; Parker and Klingeman, 1982; Wilcock, 1996). By comparing variation in macroinvertebrate drift concentrations across habitat patches where sands and gravels are alternately stable or mobilized for given flow conditions, it is possible to determine the effects on drift of "sand blasting," vs. shear stress alone, vs. habitat loss via rock rolling.

We will carry out high resolution, habitat-specific, linked drift-shear stress-grain size data collection at five fishing 'hot-spots' in Glen Canyon (e.g., "4-mile bar" at RM -4.1). These study locations were originally suggested by fishers (Gerald Meyers, personal communication) and were corroborated as drift 'hot-spots' using drift monitoring data (see figure, above). On multiple dates and flow conditions over two years, we will collect data using standardized drift methods (Kennedy and others, 2014; see Appendix, below), ADCP velocimetry for shear stress, and photographic methods for bed surface sediment. Using existing Glen Canyon-wide drift and bed shear stress data, along with bed sediment data that will be collected as part of Project A, these resulting habitat-specific relationships between invertebrate drift concentrations, shear stress, and sediment entrainment can then be scaled up to predict invertebrate drift responses at habitat patches throughout Glen Canyon. To extend these predictions down river (e.g., into habitat near the LCR of interest for humpback chub management), we will use data from ADCP measurements for shear stress at the NO drift sites, as outlined above in Project Element 2. Combined with drift and with existing channel mapping data for the LCR inflow reach from

Project 3, these data will allow drift predictions to be scaled up at a coarse scale throughout Grand Canyon, especially in reaches of particular interest for fisheries management.

For the study reach in Lower Marble Canyon—and possibly the reaches outlined above for Glen Canyon—invertebrate drift and bed condition will be investigated at a process level. In this reach, drift sampling in short downstream intervals will be conducted concurrently with repeat bed surveys and full water column multibeam echosounder data collection (described in Project 3). These repeat bed surveys will enable identification of areas of the bed where active sand transport may limit benthic invertebrate colonization and areas where colonization may occur but is subject to disturbance. The full water column data may be used to detect invertebrate drift in the water column directly.

Project Element 5.2.5. Comparative longitudinal drift studies in Upper and Lower Colorado River Basin tailwaters

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Jeffrey Muehlbauer, Research Ecologist, USGS/GCMRC
Scott Miller, Director, BLM/Utah State University National Aquatic Monitoring Center

Longitudinal patterns in invertebrate diversity, drift, and shear stress will be measured in the tailwaters of Fontenelle, Flaming Gorge, Navajo, Hoover, Davis, and Parker Dams. Sampling will occur over the course of one or two trips (single sampling), including sites extending approximately every mile from the dam to ~15 miles downstream. In addition, seasonal changes in the drift will be monitored at select stations within these tailwaters, likely proximate to discharge gages. Such seasonal monitoring in the Fontenelle and Flaming Gorge tailwaters would ideally be carried out through a collaborative agreement with other agencies, or by personnel led by Scott Miller and the BLM Bug Lab at Utah State University

Our group has developed optimized methods for monitoring drift in Glen Canyon (as outlined in the Background and in Project Element 1, above, and in the Appendix, below). However, we expect these methods to require some adjustment in the Upper Basin tailwaters, particularly in river reaches that are narrower and shallower than those present in Glen Canyon. Ideally, appropriate drift sampling methodologies would be modified for these sites in consultation and collaboration with Scott Miller, who has experience sampling drift in some of these tailwaters (Miller and Judson, 2014).

One outcome of characterizing drift in other tailwaters will be to better understand the response of the food base that is available to endangered fish species, as relevant to proposed peak flow studies for endangered fish habitat in the Upper Basin (LaGory and others, 2014). Longitudinal and seasonal drift data in these tailwaters will also be useful in comparison to emergent insect data to better link emergent insect dynamics to invertebrate drift concentrations, as discussed in Project Element 1, above. Emergent insect citizen science monitoring in these tailwaters is currently proposed by Kennedy and others, and was initiated on the San Juan River downstream of Navajo Dam in April 2014 in collaboration with Grand Canyon Youth.

Finally, these drift data will be useful in putting observed drift, habitat, and invertebrate diversity patterns in the Glen Canyon Dam tailwater in context. For example, increased understanding of drift in other tailwaters should elucidate the degree to which observed patterns and biological processes downstream of Glen Canyon Dam, such as food limitation of fish populations, zero/low EPT diversity, and rates of downstream colonization are potentially atypical. These studies may also help identify approaches for increasing invertebrate drift availability, which would benefit native and desired non-native fish populations in the Glen-Marble-Grand Canyon reach of the Colorado River.

5.3 Monitoring primary production in Glen, Marble, and Grand Canyon

A. Investigators

Theodore Kennedy, Research Aquatic Ecologist, USGS, Grand Canyon Monitoring and Research Center
Charles Yackulic, Research Statistician, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

Algae represent the base of the food web in Glen Canyon, Marble, and Grand Canyon (Cross and others, 2011; Donner, 2011; Cross and others, 2013; Wellard Kelly and others, 2013; Zahn Seegert and others, In press). In cooperation with University of Wyoming and Montana State University, we developed an approach for continuously measuring rates of algal production at the scale of the reach using detailed dissolved oxygen budgeting (Hall and others, 2010; Hall and others, 2012; Hall Jr. and others, In review). In collaboration with GCMRC's water quality monitoring program (Project X), we have been continuously measuring dissolved oxygen concentrations at 6 sites (RM 0, 30, 61, 87, 166, and 225) since 2009-2011(depending on site). A manuscript describing controls on algae production in Grand Canyon is currently in review (Hall Jr. and others, In review). In FY15-17 we will develop a manuscript describing controls on algae production in Glen Canyon. Additionally, we will continue monitoring dissolved oxygen concentrations at 6 sites in Glen, Marble, and Grand Canyon. Dissolved oxygen data from 2009-2013 have been converted to algae production estimates, but the approaches we are using to estimate algae production are extremely labor-intensive. Yackulic is a collaborator on a recently submitted USGS Powell Center proposal, the purpose of which is to develop *automated* tools for converting dissolved oxygen data into algae production estimates. Thus, if this Powell Center proposal is successful, we will also be developing automated tools for converting dissolved oxygen data to algae production estimates in FY15-17.

C. Proposed Work

C.1. Project Elements

Project Element 5.3.1 Controls of algae production in Glen Canyon

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Charles Yackulic, Research Statistician, USGS/GCMRC
Robert Payn, Research Scientist, Montana State University
Robert Hall Jr., Professor, University of Wyoming
Daily estimates of algae production in Glen Canyon have been computed from 2008-present (see figure). In FY15, we will synthesize these data and develop a manuscript describing the controls of algae production in Glen Canyon.

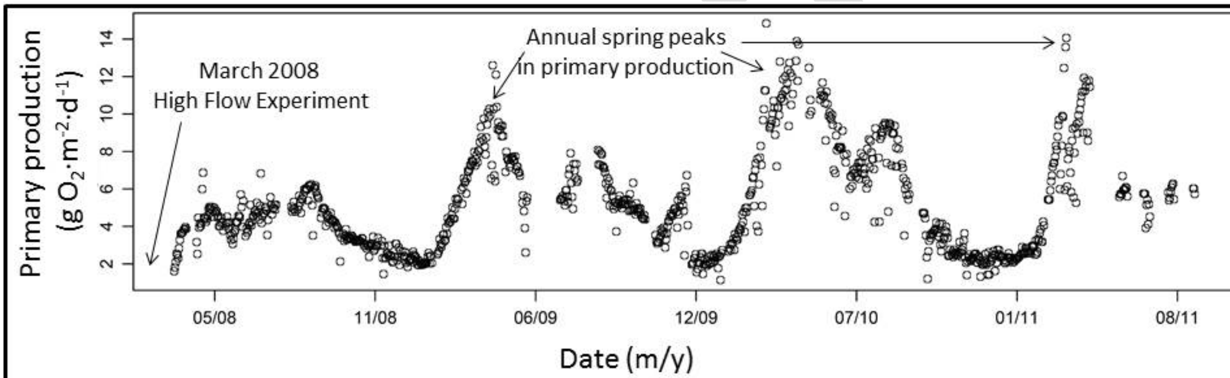

Figure showing a nearly continuous record (15 March 2008 to 10 August 2011) of primary production for the Glen Canyon tailwater ecosystem. Although dissolved oxygen monitoring commenced after the March 2008 High Flow Experiment, these data still provides insights into the effect of that Experiment on primary production in the reach. For example, 2008 is the only year in the record that lacks a strong spring peak in primary production, likely because the Experiment scoured benthic substrates and reduced primary producer biomass. Breaks in the record are because of equipment failure.

Project Element 5.3.2. Continuously monitor dissolved oxygen concentrations in Glen, Marble, and Grand Canyon

Adam Copp, Ecologist, USGS/GCMRC
Nick Voichick, Hydrologist, USGS/GCMRC

In FY15-17 we will maintain our network of continuous dissolved oxygen monitoring stations at 6 locations in Glen, Marble, and Grand Canyon (i.e., RM 0, 30, 61, 87, 166, and 225).

Project Element 5.3.3. Develop automated tools for converting dissolved oxygen data to algae production

Edward Stets, Ecologist, USGS/National Research Program
Charles Yackulic, Research Statistician, USGS/GCMRC
Robert Hall Jr., Professor, University of Wyoming

Stets is the lead, and Hall and Yackulic are collaborators, on a recently submitted Powell Center proposal, the purpose of which is to develop automated tools for converting dissolved oxygen data into algae production estimates. If the proposal is successful, one outcome of the synthesis will be automated tools developed specifically for the sites in Glen, Marble, and Grand Canyon where we have been continuously monitoring dissolved oxygen since 2008-2011.

Project 6. Mainstem Colorado River humpback chub aggregations and fish community dynamics

A. Investigators

William Persons, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Michael Dodrill, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
David Ward, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center Kirk
Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Van Haverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Rogowski, Fishery Biologist, Arizona Game and Fish Department, Research Branch
Karin Limburg, Professor, State University of New York
Brian Healy, Fishery Biologist, National Park Service, Grand Canyon National Park

B. Project Summary

Native and nonnative fish populations in Glen and Grand Canyons are key resources of concern influencing decisions on both the operation of Glen Canyon Dam and non-flow actions. To inform these decisions, it is imperative that accurate and timely information on the status of fish populations, particularly the endangered humpback chub (Gila cypha), be available to managers. A suite of adaptive experimental management actions are either underway or being contemplated to better understand the mechanisms controlling the population dynamics of fish in the Colorado River in Glen and Grand Canyons and to identify policies that are consistent with the attainment of management goals. Much effort has been and continues to be focused on humpback chub and rainbow trout (Oncorhynchus mykiss) both in the reach of the Colorado River from Glen Canyon Dam to the Little Colorado River (LCR) confluence and in the LCR itself (see Projects 7 and 9). While this work is important and meets critical information needs, it is also important to have robust monitoring of mainstem fish populations downstream of the LCR confluence. Status and trend information is needed to further understand mechanisms controlling native and nonnative fish population dynamics, determine the effects of dam operations and other management actions, and identify evolving threats presented by expansion in range or numbers of nonnative predators. This type of information is also potentially useful in assessing changes to the Federal Endangered Species Act listing status of humpback chub in Grand Canyon.

Sampling mainstem humpback chub aggregations has been conducted periodically over the last two decades. Fish were sampled by hoop and trammel nets at aggregations first described by Valdez and Ryel (1995). Most captures of humpback chub in the mainstem Colorado River have been downstream of the LCR (Persons and Van Haverbeke, in prep.). Continuing to sample for humpback chub in the mainstem river outside of the LCR and the LCR confluence area is important for monitoring the status of the Grand Canyon population of this endangered species and determining the effects of management actions like dam operations and translocations.

During the last few years the first 75 miles of the Colorado River downstream of Glen Canyon Dam has been sampled extensively for fish by several projects including the following projects in the USGS Grand Canyon Monitoring and Research Center's (GCMRC) FY2011-12 and FY2013-14 workplans:

- **E.2** Juvenile Chub Monitoring Project near the LCR confluence
  Near Shore Ecology Project in FY2011-12, and
  Project Element F.3 in FY2013-14,
- **H.2** Rainbow Trout Movement Project, a.k.a. the Rainbow Trout Natal Origins Project
  Project Element BIO 2.E18 in FY2011-12, and
  Project Element F.6 in FY2013-14,
- **D.4** System Wide Electrofishing Project
  Project Element BIO 2.M4 in FY2011-12, and
  Project Element F.1 in FY2013-14
- **H.1** Lees Ferry Trout Monitoring Project
  Project Element BIO 4.M2 in FY2011-12, and
  Project Element F.2 in FY2013-14
- **D.7** Rainbow Trout Early Life Stage Survey Project, RTELSS
  Project Element BIO 4.M2 in FY2011-12, and
  Project Element F.2.2 in FY2013-14

The remaining portion of the Colorado River downstream of Glen Canyon Dam (between approximately the LCR and Lake Mead) has been sampled as part of GCMRC's FY2013-14 workplan as described in Project **6.4**, the System Wide Electrofishing Project and Project **6.1**, the Mainstem Humpback Chub Aggregation Monitoring Project. In order to improve efficiencies and to reduce duplication of effort, GCMRC and cooperating agencies conducting fisheries monitoring and research propose to coordinate and/or combine several project elements in GCRMC's FY2015-17 workplan. These include the Juvenile Chub Monitoring project and System Wide Electrofishing effort (*see project elements 7.2 and 6.4*) as well as the Rainbow Trout Natal Origins study and Lees Ferry Trout Monitoring (*see project element 9.1*). In general, this will mean a reduction of electrofishing effort in the first 70 miles of the Colorado River downstream of Glen Canyon Dam and a focus on obtaining abundance estimates rather than catch per unit effort (CPUE) indices through the updated Lees Ferry Rainbow Trout Monitoring project (**9.1**). Systematic sampling of the mainstem Colorado River downstream of the Juvenile Chub Monitoring (*see project element 7.2*) reference site (River Mile (RM) 63-64.5) will continue under Project Elements **6.1, 6.2, 6.3** and **6.4** (*see Section 4*) and will continue to collect and analyze species composition and CPUE data.

Project 6 is comprised of eight Project Elements and includes monitoring and research projects in the mainstem Colorado River, with particular emphasis on humpback chub aggregations. Over the last several years humpback chub in the LCR aggregation have increased in abundance (Coggins and Walters, 2009; Van Haverbeke and others, 2013; Yackulic and others, 2014). Humpback chub at many other aggregations have also increased in abundance, and some aggregations appear to have increased their distribution (Persons and Van Haverbeke, *in prep.*). Recruitment to aggregations may come from local reproduction (e.g. 30 Mile aggregation; Andersen and others 2010; Middle Granite Gorge Aggregation; Douglas and Douglas, 2007), the LCR aggregation, and translocations to Shinumo and Havasu Creeks.

Annual monitoring of the status and trends of the mainstem humpback chub aggregations has been identified as a conservation measure in a recent Biological Opinion (USFWS 2011) and will continue to be monitored in Project Element **6.1,** although effort will be reduced to a single trip per year down from two trips annually in the FY2013-14 workplan. We will also continue to sample in conjunction with the National Park Service (NPS) near Shinumo Creek and Havasu Creek to assess contribution of translocated humpback chub to mainstem aggregations.

Understanding recruitment at aggregations continues to be an area of uncertainty. Humpback chub otolith microchemistry (Hayden and others, 2012; Limburg and others, 2013) was proposed as a method to determine sources of humpback chub recruitment in the FY2013-14 Work Plan. However, due to Tribal concerns about directed take of humpback chub we were unable to collect the otoliths necessary for these analyses. During FY2015-16 we plan to further evaluate the use of otolith microchemistry to identify fish hatched in Shinumo Creek, Havasu Creek, 30-Mile springs or other locations in Project Element **6.2**. We will work with NPS staff to collect water samples and otoliths from brown trout (*Salmo trutta*), rainbow trout, and other fishes sacrificed as part of their trout removal activities. We will also make use of any humpback chub incidentally killed during other sampling efforts.

Further, we will place additional emphasis on catching and marking juvenile humpback chub to assist in determining sources of recruitment to aggregations. During FY2015-16 we propose to evaluate slow shocking and seining as methods to capture and mark more juvenile humpback chub with passive integrated transponder (PIT) tags in order to assess juvenile humpback chub survival and recruitment to aggregations. This will also provide a possible method to assess dispersal of juvenile humpback chub marked in the LCR with visible implant elastomer (VIE) and PIT tags.

Project Element **6.3** will continue efforts that began in the FY2013-14 workplan to locate additional aggregations by standardized sampling and by the use of remotely deployed PIT tag antennas. GCMRC has had success in deploying relatively portable PIT tag antennas in the LCR and proposes to work with NPS and U.S. Fish and Wildlife Service (USFWS) personnel to develop antenna systems that can be deployed at mainstem aggregations and other locations to detect PIT tagged fish. If successful, these systems will provide an opportunity for collaborative citizen science with commercial and scientific river trips whereby river guides could deploy antennas overnight at camp sites in an attempt to detect PIT-tagged fish in areas not sampled during mainstem fish monitoring trips.

The System Wide Electrofishing Project (Project Element **6.4)** will continue to collect long-term monitoring data following the methods described in Makinster and others (2010) and will evaluate the efficacy of a mark-recapture approach downstream of the LCR confluence. To eliminate duplicative efforts, only limited sampling will be conducted in the areas sampled by the Rainbow Trout Natal Origins and the Juvenile Chub Monitoring projects (**9.2** and **7.2)**. We will also increase sampling effort downstream of Diamond Creek to monitor for native and non-native fishes. Continued concerns over upstream movement of non-native warmwater predatory species such as striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*) and walleye (*Sander vitreus*) from Lake Mead highlight the need to continue to monitor the river for non-native fishes. Electrofishing is effective at capturing bass and other sunfishes (Centrarchidae) and walleye, so this sampling should detect upstream movements of these species. Channel catfish on the other hand, are not effectively captured by electrofishing, so monitoring of catfish distribution by standardized angling (Persons and others, 2013) will continue during electrofishing trips. Standardized electrofishing sampling is also effective at capturing native sucker species including flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and razorback sucker (*Xyrauchen* *texanus*). Recent captures of razorback sucker downstream of Diamond Creek by this project have been widely publicized and ongoing monitoring will help document if this once extirpated species continues its apparent re-colonization of Grand Canyon.

Nonnative brown trout are effective fish predators known to preferentially prey on native Colorado River fishes including humpback chub (Yard et al. 2011). Determining the source or sources of this species in Grand Canyon will help scientists and managers better target efforts aimed at controlling this threat to native fish populations (*see project element 8.1*). Project Element **6.5** will conduct research on the use of brown trout pigment patterns to identify natal origins of brown trout; data and images will be collected during the System Wide Electrofishing Project and other projects that encounter brown trout.

One risk to the Grand Canyon humpback chub population is that it includes only one self-sustaining spawning population, the LCR aggregation. The USFWS has identified the establishment of a second self-sustaining spawning population of humpback chub as an important step towards recovery of this endangered species (USFWS 1995). Project Element **6.6** will develop plans and conduct necessary compliance activities to experimentally translocate humpback chub from the LCR to a mainstem aggregation in 2016 or later.

The Rainbow Trout Early Life Stage Survey (6.7. - RTELLS) program seasonally monitors rainbow trout egg deposition and population early life history dynamics, particularly age-0 survival in Glen Canyon. This project in particular, provides managers with an initial indication of the annual cohort strength of rainbow trout recruiting into the population. Findings from this also have relevance to the Natal Origin research project (*see project element 9.2*).

The Lees Ferry Creel Survey (6.8) monitors the health of the rainbow trout fishery and provides information on the influence of Glen Canyon Dam operations, other management actions, and natural disturbances on recreational fishing. Information on the levels of direct harvest as well as angler use and satisfaction of the important recreational fishery is also provided.

C. Proposed Work

C.1. Project Elements

Project elements include sampling humpback chub aggregations, investigating recruitment at aggregations, investigating the use of PIT tag antennas at aggregations, system wide monitoring of native and non-native fishes outside of Glen and Marble Canyons, investigating brown trout origins through examining their pigment patterns, and investigating the translocation of humpback chub to the mainstem Colorado River.

Project Element 6.1. Monitoring humpback chub aggregation relative abundance and distribution

William Persons, Fishery Biologist, USGS/GCMRC
D.R. Van Haverbeke, Fishery Biologist, U.S. Fish and Wildlife Service
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park

This Project Element will concentrate on monitoring status and trends of humpback chub aggregations not associated with the LCR. This Project Element will build on work conducted in 2013 and 2014. Persons and Van Haverbeke (*in prep*) have been able to detect long term changes in relative abundances by pooling data into 5-year blocks, but were unable to provide defensible annual abundance estimates from the aggregations (Persons and Van Haverbeke, GCMRC Annual Reporting Meeting, 2014). Sampling will be reduced from two trips to one trip, but will include sampling by seine and nearshore electrofishing which has been effective capturing juvenile fish near the LCR confluence (J. Korman, *pers. comm*.). While sampling trips will concentrate on known aggregations and translocation locations, several days of effort will also be devoted to sampling areas associated with springs and faults thought likely to harbor humpback chub.

The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.2. Humpback chub aggregation recruitment studies

Michael Dodrill, USGS/GCMRC
Karin Limburg, State University of New York
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park

Recent apparent increases in relative abundance of humpback chub at mainstem aggregations (Persons and Van Haverbeke, *in prep.*) suggest that local recruitment may be occurring at some sites. While it is known that the LCR serves as a source of humpback chub into the mainstem Colorado River and that some of these fish move downstream and likely survive, there may be other areas with local reproduction that act as sources of recruitment (Andersen and others, 2010). Although we will not deliberately sacrifice humpback chub to collect otoliths for microchemistry analysis, we will work with NPS to collect surrogate species from tributaries of interest and analyze samples for unique chemical signatures that might be associated with particular tributaries. We will continue to work with all projects to collect and preserve any humpback chub incidentally killed during sampling. This Project element will attempt to collect juvenile humpback chub in backwaters and other nearshore areas by seining and electrofishing.

Fish will be examined closely for VIE tags (see Project **7.3**) and PIT tags to evaluate possible sources of recruitment. The project will also acquire and explore the use of a thermal imaging infrared camera to help identify sampling locations at warm springs in the mainstem. The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.3. Monitoring mainstem humpback chub aggregations using PIT-tag antenna technology

Kirk Young, Fishery Biologist, U.S. Fish and Wildlife Service
D.R. Van Haverbeke, Fishery Biologist, U.S. Fish and Wildlife Service
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
William Persons, Fishery Biologist, USGS/GCMRC

The objective of this project is to investigate use of remotely deployed, portable PIT-tag antennas to monitor mainstem aggregations of humpback chub, especially at mainstem translocation sites. Two long standing goals of biologists monitoring humpback chub in Grand Canyon are to develop indices to monitor the abundance or relative abundance of humpback chub, and to reduce handling of fish. This project will evaluate use of stationary, temporary PIT-tag antennas to detect humpback chub and other PIT-tagged fish in the mainstem Colorado

River. Deployment of antennas at known aggregations may also help answer questions about residencies of humpback chub within and among aggregations, potential gene flow among the aggregations, and movement. It is believed that given strategic placement of antennas at sites such as near Shinumo Creek, we may be able to increase the detection rates of tagged fish, and possibly decrease the amount of trammel netting or hoop netting. In addition, remote antennas could be deployed near future translocation sites in the mainstem. If proven feasible, similar technology might also be used in a Citizen Science approach working with commercial and science river guides to deploy PIT-tag antennas at overnight campsites.

Investigators and involved agencies will coordinate selection of appropriate locations, obtain environmental clearances, coordinate with tribes and install up to three experimental remote solar powered PIT tag antennas at known aggregations. Site location, materials, and temporary installation strategies will be deployed so as to minimize visual and Grand Canyon visitor detection. Possible sites include near aggregations at 30-Mile, the Shinumo Creek Inflow, Middle Granite Gorge, the Havasu Creek Inflow, or near RM 214. Sites for antennas would be located at aggregations that have historically yielded a high number of chub. The ability to keep antennae equipment safe and out of view of the public would also be a factor in site selection. Antennas will be downloaded and serviced from existing GCMRC river trips and data will be evaluated for incorporation into the GCRMC fish database. The project will produce annual progress reports and recommendations for use of the methods as part of long-term monitoring efforts.

Project Element 6.4. System Wide Electrofishing

David Rogowski, Fishery Biologist, Arizona Game and Fish Department
William Persons, Fishery Biologist, USGS/GCMRC

The primary objective of this project element is to continue providing data on the longitudinal distribution and status of the fish community during a transitional period (FY2015-2016) prior to implementation of a revised long-term monitoring program.

Sampling in the current SWEF project consists of two annual spring electrofishing trips and one fall trip (i.e., exceptions werein 2007 when one spring trip and one fall trip were conducted and 2011-12, when only a single annual spring trip was conducted). This project uses CPUE indices to track relative status and trends of the most common native and nonnative fish species in the mainstem, which includes sampling downstream from Diamond Creek. In order to avoid duplication of effort with the Natal Origins research project, the SWEF will not sample in the same reaches as that project. Instead, sampling in Marble Canyon will occur in areas of interest (*see project element 9.2*), but not sampled by the Natal Origins Research Project (e.g., near the confluence of Nankoweap Creek). This Project will sample downstream of the Juvenile Chub Monitoring (*see project element 7.2*) reference site (RM 63-64.5) starting below Lava-Chuar rapid (RM 66.0) and will provide information on species composition and relative abundance. In addition, sampling effort will increase downstream of Diamond Creek from one fall trip to one spring and one fall trip to focus on nonnative and native fish upstream of Lake Mead.

Difficulties arise in fish monitoring programs as a result of the rarity of many species, life history characteristics that contribute to patchy distributions and variable densities in time and space, low and variable capture probabilities, and the inability to use consistent sampling gear among all occupied habitats. With the exception of mark-recapture based abundance estimators, most fish monitoring efforts produce relative indices of abundance (e.g., catch rates, presence/absence) for monitoring the status and trend of a fish community. Yet, in order for catch rates (i.e., CPUE) to be effective as a monitoring metric, capture probabilities (probability of an animal being caught) need to be known rather than just assumed to be constant across sites or sampling periods. When capture probabilities vary due to factors like trout densities or turbidity levels (Korman and others unpublished data), catch rate indices can become an inaccurate proxy for fish abundance. Factors like these are a common phenomenon in Grand Canyon that leads to estimation biases in fish abundance. For example, catch rates are likely to underestimate actual abundance at high trout densities (i.e., Glen Canyon) and overestimate actual abundance under low trout densities (i.e., below the LCR). Therefore, reliance on this type of metric solely becomes problematic, particularly when management decisions require a degree of accuracy (e.g., Biological Opinion triggers). This can only be resolved if capture probabilities are estimated using mark-recapture procedures.

We propose that during this interim period a hybrid approach be used; one that maintains some continuity with past SWEF sampling, and also evaluates the applicability of using a mark-recapture program, particularly in the downstream reaches. One downstream sampling trip will use the standard SWEF sampling (single-pass) protocol with a stratified random sampling design used in site selection (400-500 sites/trip) (as described in Makinster and others 2010). To avoid sampling overlap with NO, sampling will occur below Lava-Chuar (RM 66). The other downstream sampling trip incorporates a number of 2-pass mark-recapture studies using similar sampling protocols as developed part of the Natal Origin research project (Korman 2012). During this interim period, these data will be used in conjunction with other mark-recapture and CPUE data to develop a set of estimation procedures for conducting simulations to redesign the long-term fishery monitoring programs inclusive of the Lees Ferry Rainbow Trout and the SWEF programs. The redesigned proram will be evaluated by an independent protocol evaluation panel (*see project element 8.3*). Sampling efforts as part of the SWEF program will continue sampling the downstream sections including below Diamond Creek. Three trips will be conducted annually during late April-May, late May-June, and October (Diamond Creek to Pierces Ferry) to maximize water clarity conditions for electrofishing, particularly in the downstream reaches.

This project will produce trip and annual reports with recommendations for long-term monitoring.

Project Element 6.5. Brown trout natal origins through body pigmentation patterns in the Colorado River

David Rogowski, Fishery Biologist, Arizona Game and Fish Department, Research Branch
Michael Collyer, Assistant Professor, Western Kentucky University
William Persons, Fishery Biologist, USGS/GCMRC

Non-native brown trout have been introduced into the Colorado River and tributaries and are maintaining a naturally reproducing population. Brown trout are highly piscivorous and negatively affect the imperiled native fishes of the Colorado River drainage (Yard et al. 2011). Much effort has been invested in control and removal of brown trout and other non-natives (Coggins et al. 2011, Yard et al 2011). It is thought that the bulk of reproduction and recruitment occurs in the tributaries (e.g., Bright Angel Creek). However, it is not known whether Bright Angel Creek is the main source of brown trout into the system, if there are other major recruitment areas (mainstem or tributaries), or even if there is a large panmictic population or a number of smaller populations. For salmonids there appears to be a heritable basis for coloration as well as a phenotypic response based on environment. It is thought that background color is based on environment (Westley et al 2013), while spotting characteristics have a heritable basis

(Blanc et al. 1982, 1994, Skaala and Jørstad, 1988, Skaala et al. 1992). It has been shown that one can discriminate between native and hatchery brown trout as well as hybrids based on the number and shape of parr marks (Blanc et al. 1982, Mezzera et al 1997). One can also discriminate different strains of brown trout based on coloration and spotting patterns (Aparico et al 2005). Thus it might be possible to determine if brown trout within the Colorado River system are one panmictic population or comprised of various metapopulations based on differing phenotypic characteristics.

We propose to quantify the colorations and spotting patterns of brown trout at various locations within the Colorado River and tributaries between Glen Canyon Dam and Lake Mead. Digital images of fish will be taken with a Munsell color chart and a scale. The shape, color, size, number, and location of spots (and parr marks for juvenile fish) will be quantified using a digital imaging program (e.g., ImageJ, tpsDIG2).

The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.6. Mainstem translocation of humpback chub

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
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Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
William Persons, Fishery Biologist, USGS/GCMRC

A long standing goal of managers has been establishing a second spawning population of humpback chub in Grand Canyon. The USFWS issued a Biological Opinion (USFWS 1995) concerning the preferred Modified Low Fluctuating Flow alternative on the Operation of Glen Canyon Dam EIS (USBR 1995), whereby one element of the reasonable and prudent alternative (RPA) was to "Make every effort to establish a second spawning aggregation of humpback chub downstream of Glen Canyon Dam."

To address this RPA, Valdez et al. (2000) produced a research and implementation plan for establishing a second spawning population of humpback chub in Grand Canyon. The conclusions in Valdez et al. (2000) were: 1) the highest chance for success of establishing a viable mainstem spawning population for humpback chub would be in the mainstem itself, and 2) experimental translocations into side tributaries should be conducted. The second recommendation of Valdez eta al. (2000) has been implemented with promising success at Shinumo and Havasu Creeks. This project would attempt to more directly address the first recommendation of Valdez et al. (2000).

Humpback chub have been successfully translocated into Shinumo and Havasu Creeks, and emigrants from these tributaries have augmented their respective mainstem aggregations (Persons and Van Haverbeke, *in prep*). These translocations are thought to have been successful in augmenting mainstem aggregations in part because the tributaries provide suitable rearing habitat for juveniles before some emigrate into the mainstem. Many translocated humpback chub that have emigrated from Shinumo and Havasu Creeks and were subsequently captured in the mainstem have been sub adults (<200 mm), suggesting that direct augmentation of small humpback chub into the mainstem may be feasible. This approach could be an avenue to augment aggregations or other groups of humpback chub not located near tributaries.

Approximately 250 juvenile (<100 mm) humpback chub will be collected annually from the LCR as part of Project **F.1**. Fish will be transported out of the LCR by helicopter and then transported to Southwestern Native Aquatic Resources and Recovery Center (SNARRC) along with humpback chub designated for Shinumo and Havasu Creeks. Once at SNARRC, fish will undergo quarantine procedures and reared for a year until reaching ~150 mm TL. Fish will be PIT tagged, and transported back to Grand Canyon. They will then be transported either by boat or by helicopter to a release site. The eventual release site will be decided upon by management agencies, with input from cooperators. One possible location would be within, or adjacent to, the Pumpkin Spring aggregation. This area may be favorable for humpback chub rearing due to the presence of springs, several large eddy complexes, at least one large backwater, a large cove, several gravel producing debris fan inflows, and relatively warm water.

Fish will be tempered and soft released in large eddy complexes, backwaters or slow current areas. Release of fish would likely occur in September or possibly earlier if it is possible to grow chub to a sufficient size at SNAARC. Annual monitoring would occur during mainstem aggregation trips. Additional monitoring could be possible if release occurs near the Pumpkin Spring aggregation, and upriver access was granted from Diamond Creek. The project will produce annual progress reports and one peer reviewed publication at project completion.

Project Element 6.7 Rainbow Trout Early Life Stage Survey

Luke Avery, Fishery Biologist, USGS, GCMRC
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The objective of the RTELSS study is to monitor the response of the age-0 population of rainbow trout in Lees Ferry to variations in Glen Canyon Dam operations and to naturally occurring disturbances to the CRe in Glen Canyon.

Understanding of the effects of various physical and biological conditions on the age-0 rainbow trout population will enable better management practices to attain desired rainbow trout abundance and population structure. Monitoring of the age-0 population also provides early indication of potential changes to the juvenile and adult rainbow trout population, providing the potential for early response to undesirable conditions. This monitoring will answer the following questions: 1) How do changes in the conditions (e.g., bed texture, flow, aquatic vegetation, and sediment supply) of the Colorado River in Glen Canyon effect the age-0 population of rainbow trout? 2) How can dam operations be experimentally evaluated to determine whether or not they might be used to manage the rainbow trout population via influences on the young-of-the-year population?

The RTELSS program was initiated in January 2003 to monitor the effects of the nonnative fish suppression flows (NFSF) that occurred during January through March from 2003-2005 (Korman and others, 2005). Since then it has provided information on the response of the age-0 rainbow trout population to higher flow dam releases that have occurred in March through June 2008, and falls of 2011, 2012, and 2013, as well as the response to the equalization flows that occurred in spring through fall 2011. An understanding of the response of the age-0 rainbow trout population to these flow events has provided a more mechanistic understanding of correlated changes that have occurred in the adult rainbow trout population and downstream emigration events that have been associated with some of those changes (Korman and others, 2012, Makinster and others, 2011, Melis and others, 2012). Maintaining the RTELSS as a monitoring program ensures sufficient data will be available to detect a response of the age-0 rainbow trout population to changes in the CRe within Glen Canyon, whether those changes in the system be by scientific design or not. Understanding of the response of age-0 rainbow trout to various conditions and events may enable management to better maintain the balance between a blue ribbon rainbow trout fishery and the welfare of the endangered native humpback chub.

The RTELSS program monitors egg deposition in winter and early spring and proceeds with monitoring of population dynamics through summer, fall, and early winter. Monitoring of egg deposition consists of 9-10 redd surveys conducted from December through May. Data collected provides information on the timing and magnitude of the spawn that provides the foundation for the year's cohort of fish. Larval and juvenile fish sampling (backpack and boat electrofishing) trips occur once a month in June-September and November. Data collected provides information on hatch success and early survival, as well as survival through the year. Otoliths extracted from specimens collected across trips provide information on growth and hatch distribution. Survey, sampling, and data analysis details can be found in in Korman and others, 2009, and Korman and others, 2011.

Project Element 6.8. Lees Ferry Creel Survey

David Rogowski, Fishery Biologist, AGFD
William Persons, Fishery Biologist, USGS, GCMRC

The objective of this project element is to evaluate how changes in the conditions of the Colorado River in Glen Canyon affect angler effort, catch and harvest on an annual basis.

The blue ribbon rainbow trout fishery of Lees Ferry has been identified as a key resource of the Colorado River in Glen Canyon under the purview of the Glen Canyon Dam Adaptive Management Program (GCDAMP) and so must be maintained. The Lees Ferry trout fishery is located in the tailwater portion of the Colorado River ecosystem from Glen Canyon Dam to the Paria River. The status and trends of the fishery are regulated by biotic and abiotic mechanisms that may in turn be affected by the operations of Glen Canyon Dam.

Creel surveys are an effective tool to monitor a variety of metrics such as: the impact of recreational fishing on the fishery (harvest rates), angler use (indirect measure of economic impact), and angler satisfaction (Malvestuto 1996). Creel surveys are also an effective way to maintain an active presence with the fishing public, provide needed outreach, as well as feedback and observations about the fishery from the public. Anglers are often the first to notice changes in fish health or invasive species. Angler creel surveys will be conducted to estimate angler effort, catch and harvest. Monitoring basic angler statistics including angler usage (anglers/year), catch-per-unit-effort, and harvest rates provide information necessary to assess the status of these resources and inform the Adaptive Management Program.

Project 7. Population Ecology of Humpback Chub in and around the Little Colorado River

A. Investigators

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B. Project Summary

During 2013-14 we developed models that integrate data collected in the Little Colorado River (LCR) with data collected by the juvenile chub monitoring (JCM) project to provide a holistic picture of humpback chub (*Gila cypha)* population dynamics (Yackulic and others, 2014). This manuscript suggests that chub movement between the LCR and Colorado River prior to adulthood is relatively rare, with the exception of young-of-the-year outmigration and that growth and survival rates are very different in these two environments. This journal article also identified the need for studies of trap avoidance among older humpback chub in the LCR, a need that can potentially be addressed by increased use of remote technologies for detecting humpback chub. We then used a modified version of these models to explain interannual variability in mainstem growth and survival in terms of monthly temperature and estimated rainbow trout (*Oncorhynchus mykiss*) abundances in order to support the development of the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement and address the key uncertainty surrounding the relative importance of rainbow trout and temperature in humpback chub population dynamics (Yackulic and others, in prep.). While parameter estimates in these models are based on field data collected in the LCR and JCM, this modelling was aided conceptually by lab experiments exploring impacts of trout and temperature on chub growth and survival (Ward and others, in prep).

Simulating future dynamics under alternative management strategies as part of the LTEMP process highlighted the importance of uncertainty associated with several key population processes, especially the production and outmigration of young-of-the-year humpback chub from the LCR. To address this uncertainty, already identified in the Grand Canyon Monitoring and Research Center's workplan for Fiscal Years (FY) 2013-14, we initiated juvenile humpback chub marking with visible implant elastomer (VIE) tags in the LCR during early July, a period when humpback chub are just becoming large enough to have a reasonable chance of surviving in the mainstem. Although LTEMP obligations have delayed a formal analysis of these data, preliminary work suggests that this effort will allow us to estimate juvenile humpback chub abundance and outmigration with acceptable precision. We also analyzed data collected by the U.S. Fish and Wildlife Service (USFWS) from 2001-2013 to characterize spatio-temporal variation in survival, growth and movement of sub-adult humpback chub in the LCR (Dzul and others, in review). This work suggests both that winter growth is strongly and negatively correlated with the extent of winter/spring flooding and that habitat quality for sub-adult humpback chub is better in upper reaches of the LCR. This follows work by Vanhaverbeke *and others* (2013) indicating that when winter/spring flooding was minimal, juvenile production was poor. Other activities during FY 2013-14 included pilot work to determine the best ways to characterize spatio-temporal variation in the food base in FY2013, with plans to rigorously sample the LCR food base in calendar year 2014.

In FY2015-17, we will: (a) continue to monitor humpback chub in the LCR and Colorado River reference site (river mile (RM) 63.0-64.5) and to mark young-of-year humpback chub throughout the lower 13.6 km of the LCR in July, (b) develop field and analytical techniques to better use remote technologies for detecting passive integrated transponder (PIT) tags to address questions of trap avoidance and to potentially minimize future handling of chub, (c) develop new non-lethal tools for measuring the health and condition of humpback chub in the field, (d) undertake targeted, cost-effective research to understand mechanisms underlying observed population processes, including the roles of high CO_2 at base flow, gravel limitation, parasites, and the aquatic food base, and (e) continue to develop models that integrate findings from the above projects. The proximate goals of these activities is to better understand the relative roles of LCR hydrology, water quality, intraspecific and interspecific interactions, and mainstem conditions in humpback chub juvenile life history and adult recruitment, as well as to better estimate the current adult abundance. The ultimate goal of these activities is to continue to develop tools that allow us to better predict the impacts of dam operations and other management activities on humpback chub populations as well as appropriately account for uncertainty in these predictions. Specific questions of interest include:

1. To what extent does young-of-the-year humpback chub production and outmigration from the LCR vary between years and how is this variation driven by LCR hydrology and intraspecific interactions (i.e., cannibalism and competition)?
2. What are the drivers of interannual and spatial variation in survival and growth of juvenile and sub-adult humpback chub? In particular, what are the roles of LCR and mainstem conditions in the overall trajectory of the population?
3. Are there factors, such as heterogeneity in skip-spawning rates, heterogeneity in adult humpback chub capture probabilities in the JCM, or trap avoidance in the LCR that bias estimates of the adult population size and population processes?

Juvenile humpback chub are the most sensitive life stage to mainstem conditions and an understanding of their life history is the key to predicting the influence of dam operations on this species. Prior to the Near Shore Ecology (NSE) project (2009-2011) and the more recent JCM project (2012-current), our understanding of humpback chub early life history was limited to back-calculations of cohort strength (number of fish surviving to adulthood from a given hatch year) derived from abundance estimates of humpback chub greater than 200 mm and believed to be four years old (Coggins and others, 2006; Coggins and Walters, 2009). However, given the disparity in growth rates between humpback chub living in the LCR and Colorado river (Yackulic and others, 2014) this approach was almost certainly misleading as humpback chub could be anywhere from 4 – 10 years old when they reach 200 mm depending on where they had spent most of their time (LCR or mainstem Colorado River) and what environmental conditions had been like in those locations.

Since 2009, we have developed the field techniques (including a fixed reference site in the Colorado River) and analytical methods that allow us to understand humpback chub early life history in the detail required to begin to tease apart the effects of variation in population processes caused by mainstem temperature, trout abundance, and conditions in the LCR. For example, in support of the LTEMP process we were able to fit relationships between monthly temperature and estimated rainbow trout abundance and juvenile humpback chub survival and growth using only data from 2009-2013 that accurately predicted trends in adult humpback chub numbers from 1989-2009. While there is still room for improvement in these models, this represents a dramatic step in our ability to predict the consequences of management options.

While conditions in the LCR are not directly affected by dam operations, they nonetheless play a vital role in determining the degree to which temperature and rainbow trout numbers in the Colorado River must be managed. For example, if juvenile humpback chub production and export are high, this may suggest less need for rainbow trout management and/or lower flows to increase water temperatures in the mainstem. Alternatively, a better understanding of the factors leading to increased humpback chub production could provide decision makers opportunities to strategically implement management actions in years when they would have the largest effect. For example, the 2000 Low Steady Summer Flow experiment may have been ineffective simply because it followed two years of potentially minimal production of juvenile chub. Improved information about the drivers of humpback chub population dynamics could have helped managers and scientists plan this experiment such that it occurred when conditions were more likely to result in a detectable response. Likewise, management actions such as mechanical removal of nonnative fishes will be much more effective if they occur in years of high humpback chub production. If variation in production is primarily driven by exogenous factors (e.g., extent of flooding) as opposed to endogeneous factors (e.g., competition between cohorts) this also has implications for long-term population dynamics.

With respect to adult humpback chub, key uncertainties revolve around our understanding of capture probability and movement. In particular, heterogeneity in capture probability in the LCR caused by some adult humpback chub (especially potential residents) avoiding hoop nets could lead to underestimates of abundance. At the same time, the potential for temporary emmigration in the JCM reach is a cause for concern and could lead to overestimates of abundance. Lastly, a better understanding of skip-spawning in adult humpback chub is essential because many adults are only vulnerable to capture during spring sampling in the LCR and thus inferences about their survival and abundance depends on assumptions about the skip-spawning process. Answering the above uncertainties is dependent both on new data streams from remote tag readers and intellectual investment into developing the appropriate models to incorporate this information and test hypotheses.

C. Proposed Work

C.1. Project Elements

Project Element 7.1. Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River

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Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office David R. Van Haverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Rogowski, Fisheries Biologist, Arizona Game and Fish Department

The most efficient way to sample adult humpback chub that spawn in the LCR is during the spring as capture probabilities in the LCR for adults are much higher than in the mainstem. Fall sampling provides us with yearly estimates of the abundance of young-of-the-year that have not left the LCR and is the closest we have to a long-term dataset of juvenile humpback chub production. Data collected during these trips are all used to estimate spring and fall closed population abundance for various size classes of humpback chub (> 150 mm and > 200 mm total length (TL)), and during some years provides abundance estimates of other native fishes (Coggins and others, 2006; Van Haverbeke, 2010). The project also marks juvenile humpback chub (< 100 mm TL) with Visible Implant Elastomer tags in the fall in conjunction with Juvenile Chub Monitoring project (Project Element E.2) and the July LCR marking project (Project Element E.3) to improve our understanding of juvenile humpback chub production and outmigration. This is an ongoing project since 2000 and the monitoring was identified as a necessary component in the 2011 Environmental Assessment for Non-Native Fish Control Downstream from Glen Canyon Dam and associated Biological Opinion (Bureau of Reclamation, 2011). The specific objectives for 2015-17 (similar to objectives for previous years) are:

1. Determine length stratified Chapman modified Peterson closed population estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm) in the lower 13.57 km of the LCR during the spring and fall.
2. Generate a population estimate of age 0 humpback chub (40-99 mm) during fall.
3. Collect data on PIT tagged fish in support of humpback chub population modelling (Project Element 7.10).
4. Collect additional data on fishes in the LCR such as size, species, sexual condition and characteristics, and external parasites (i.e., Lernaea cyprinacea).

Modifications to this project include use of experienced biologists and expansion of remote sensing efforts throughout the LCR (see Project Element 7.4). Specifically, we will replace three volunteer positions with paid staff, resulting in increased project costs for fiscal years 2015-2017. Working with partners, we propose amalgamation of Arizona Game and Fish Department's (AGFD) lower 1200 meter monitoring efforts into LCR mark-recapture effort (Spring and Fall). This approach avoids the need to increase overall LCR long term monitoring costs and facilitates deployment of portable remote PIT tag readers to assess humpback chub demographics across the three sample reaches constituting the occupied 13 km of the LCR. We also propose to involve Navajo Nation or other Tribal members in sampling activities and have included funding to support a temporary field position (four 10-day trips). Methods will follow those used from 2000-2014 (described in Van Haverbeke and others, 2013). Arizona Game and

Fish Department will provide experienced biologists to assist with hoop net efforts, and be responsible for small PIT tag antennas deployed near each camp.

Project Element 7.2. Juvenile Chub Monitoring in the mainstem near the Little Colorado River Confluence

Mike Yard, Fishery Biologist, USGS/GCMRC
Josh Korman, President, Ecometric Research, Inc.
Maria Dzul, Fishery Biologist, USGS/GCMRC
Charles B. Yackulic, Research Statistician, USGS/GCMRC

This project provides the data to estimate survival, growth and abundance of juvenile humpback chub for a reference reach in the mainstem Colorado River. It also provides additional passes to estimate rainbow trout and brown trout abundance in this same reach (the reference reach is sampled using rainbow trout specific methods as part of the Natal Origins project; Project Element 9.4). Data from this project, in addition to temperature collected near the LCR confluence through Project 2, will be used in Project Element 7.10 to refine our understanding of the effects of temperature and trout on humpback chub survival and growth. Recent progress in our understanding of trout and mainstem temperature effects on humpback chub population dynamics are solely dependent on data collected through this project and its precursor, the Near Shore Ecology project. Recaptures of VIE marked humpback chub in the reference reach, especially humpback chub marked through the July LCR sampling (Project Element 7.3), are crucial to understanding movement out of the LCR into the Colorado River. Obtaining rainbow and brown trout abundance estimates between RM 63-64.5 were identified as necessary activities in the 2011 Environmental Assessment for Non-Native Fish Control Downstream from Glen Canyon Dam and associated Biological Opinion (Bureau of Reclamation, 2011). The metrics are included in the suite of triggers identifying when to implement mechanical removal of nonnative fish to protect humpback chub. Continued annual assessments of juvenile humpback chub survival rates and abundance in the mainstem using methods developed in the Near Shore Ecology Study will provide key metrics by which management actions such as rainbow trout removal will be evaluated.

Project Element 7.3. July Little Colorado River juvenile humpback chub marking to estimate production and outmigration

Maria Dzul, Fishery Biologist, USGS/GCMRC
Charles B. Yackulic, Research Statistician, USGS/GCMRC
Luke Avery, Fishery Biologist, USGS/GCMRC
David Ward, Fishery Biologist, USGS/GCMRC
Mike Yard, Fishery Biologist, USGS/GCMRC

The objective of this project element is to determine how rates of juvenile humpback chub outmigration vary between years and the degree to which outmigration rates are driven by juvenile densities or the strength of flooding associated with summer monsoons. This project also seeks to estimate the abundance of young-of-the-year humpback chub in the LCR prior to the most significant period of outmigration (July-September). As mentioned above, juvenile production and rates of juvenile outmigration are two of the largest uncertainties in population models of humpback chub that spawn in the LCR and thus uncertainty in these population processes hampers efforts to determine how much management is required to maintain healthy adult populations. Uncertainty in juvenile production and outmigration was one of the largest uncertainties in predicting humpback chub responses to alternatives during the LTEMP process. Previous research suggests that rates of outmigration are relatively high (Yackulic and others, 2014). It should be noted, however, that these estimates were based on marks put out only in the lowest portion of the LCR and were concentrated in years that likely had high levels of export (2011 & 2012), thus may have biased estimates high. Preliminary estimates suggest that outmigration by the 2013 cohort was lower and that the size of this cohort may have be relatively small. Lastly, if rates of recovery of juvenile humpback chub marked during July sampling are substantially lower at non-LCR aggregations (Project 6) as opposed to in the JCM reach (Project Element 7.2) this could be taken as evidence of local reproduction at aggregations.

Sampling during July relies on three gear types, seining, dip nets and hoop nets to capture juvenile humpback chub at each of the three sample reaches and humpback chub between 40-100 mm are given VIE batch marks (humpback chub over 100 mm are scanned for PIT tags according to the standard protocol, however, the focus of our efforts is on juveniles, that is humpback chub under 100 mm in total length).

Project Element 7.4 Remote PIT tag array monitoring

William Persons, Fishery Biologist, USGS/GCMRC

The objectives of this project are to provide data to test hypotheses about trap avoidance and humpback chub movement and to potentially provide a future alternative to decrease handling of adult humpback chub. This has been an ongoing effort since 2009, with lapses and equipment failures during parts of 2010 and 2011. The project has installed two PIT tag antenna arrays in the LCR approximately 2 km upstream from the confluence with the mainstem Colorado River. The antenna arrays read and record PIT tag codes from marked fish along with a date/time stamp as they pass near anntennas anchored to the river bottom. These data can be used within population models as well as to provide information on timing of movement and survival of PIT tagged native fishes. Antenna detection efficiency has varied greatly and was estimated to be 6 – 42%. Work completed during FY2012-FY13 by a Colorado State University graduate student is expected to result in a thesis during 2014. Preliminary findings suggests that skip-spawning by adult humpback chub is Markovian (i.e., individuals that spawned in the previous year are less likely to spawn than individuals that did not spawn). During FY2015-17 we plan to maintain the existing antenna arrays and to deploy three portable antennas approximately 9 km upstream from the LCR mouth to attempt to better assess movement and avoidance of hoop nets.

Project Element 7.5. Food web monitoring in the Little Colorado River

Jeff Muehlbauer, Aquatic Ecologist, USGS/GCMRC
Ted Kennedy, Aquatic Ecologist, USGS/GCMRC
Charles B. Yackulic, Research Statistician, USGS/GCMRC

The objectives of this project are to characterize invertebrate drift, benthic densities and emergence throughout the perennial (lower 21 km) reach of the LCR over various seasons and to test whether emergence techniques are an appropriate technique for long-term monitoring in this and other tributaries. We suspect that the amount of invertebrates available for consumption by fish, and humpback chub in particular, varies longitudinally because of work suggesting higher humpback chub growth above Chute Falls (Stone and others, *in prep*) as well as higher growth and abundance of subadult humpback chub in Coyote and Salt camps relative to Boulders camp (Dzul and other, *in review*; Vanhaverbeke and others, 2013). Preliminary data collected in July

2013 suggests that emergence below the Chute Falls (no sampling occurred above Chute Falls) increases at stations located further from the confluence. A better understanding of the food base in areas that support high densities of humpback chub growing quickly may aid in determining the carrying capacity within the LCR as well as in tributaries considered for translocation efforts.

This project is a continuation of a project begun in FY 2013-14. Logistical constraints and weather-related issues ultimately precluded the total completion of this project within that timeframe, and we therefore propose to continue the project into FY 2015 and possibly the first months of FY 2016 in order to provide better quality results. Sampling will occur quarterly (December, April, June, and September), and monthly in the period of highest humpback chub growth (April to September), with additional opportunistic samples occurring once per year as soon as possible after the first annual summer monsoon flood. Sampling will involve the deployment of sticky traps (Smith and others, 2014) in consistent locations and habitat conditions throughout the perennial 21 km reach of the LCR, from Blue Spring to the confluence with the Colorado River. Light traps (Kennedy and others, 2013) are also set out at camps in the evenings. At the three main camps (Salt, Coyote, Boulders) and at major aquatic habitat changes (Blue Spring, Chute Falls, confluence), benthic samples are also taken using standard D-nets, emergence traps are deployed over the water, infall traps for organic matter and terrestrial insects are deployed at the water's edge, and aquatic habitat is quantified based on visual estimates of percent cover of algae and using pebble counts (Wolman, 1954). Finally, temperature, conductivity, and dissolved oxygen are measured using data loggers deployed above and below the Chute Falls/Atomizer complex and near Salt and Coyote camps.

Project Element 7.6. Potential for gravel substrate limitation for humpback chub reproduction in the LCR

Maria Dzul, Fishery Biologist, USGS/GCMRC
Jeff Muehlbauer, Aquatic Ecologist, USGS/GCMRC
David Ward, Fishery Biologist, USGS/GCMRC
Charles B. Yackulic, Research Statistician, USGS/GCMRC

The objectives of this project element are to characterize year-to-year variation in gravel availability in the LCR and determine whether lack of gravels limits juvenile humpback chub production in certain years. VanHaverbeke and others (2013) showed that juvenile humpback chub production in the LCR has been lower during the period 2001-2012 during years without significant winter/spring flooding. Earlier work suggested that increases in discharge in the LCR exposes fresh gravel deposits that are ideal for development of humpback chub eggs (Kaeding and Zimmerman 1983) and that humpback chub spawning activity is associated with clean gravel deposits (Gorman and Stone 1999). Accordingly, scarcity of gravel substrates may play a significant role in humpback chub population processes, however, there is little direct evidence to determine whether the cause of low recruitment is due to scarcity of fresh gravel deposits. Evaluating how low spring discharge affects humpback chub recruitment is especially important because climate projections predict decreased precipitation throughout the southwestern USA (Seager and others 2007), and thus years with low snowmelt may become increasingly common in northern Arizona. This project will involve annual substrate mapping and monitoring using bed surface random-walk pebble counts (Wolman 1954) in a reference reach of the LCR conducted every year in conjunction with spring LCR monitoring (Project Element 7.1). In addition, we will conduct gravel tray experiments to determine the sediment characteristics that are required for humpback chub egg deposition and survival.

Project Element 7.7. Evaluate CO_2 as a limiting factor early life history stages of humpback chub in the Little Colorado River

David Ward, Fishery Biologist, USGS/GCMRC
Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office

The objective of this project is to evaluate the extent to which high levels of dissolved CO_2 in the LCR at base flow impacts early life history stages of humpback chub. High levels of dissolved CO_2 in water are known to negatively affect fish populations and have been hypothesized to constrain humpback chub to the lower 14.2 km of the LCR in Grand Canyon (Mattes 1993, Robinson and others 1996, Kaeding and Zimmerman 1983). Elevated CO_2 levels decrease the ability of a fish's hemoglobin to transport oxygen and can compromise respiration in fishes. The safe or accepted levels of CO_2in water depend upon fish species (Basu 1959). In general, levels above 60 ppm are avoided by fish and can be detrimental to fish health (Alabaster and others 1957, Reviewed in Heinen and others 1996) with early life history stages of fish being most sensitive (Baumann and others 2012). At base flow CO_2 levels near the confluence of the LCR are often above 100 ppm and increase upstream (Robinson and others 1996, Dennis Stone FWS, personal communication). Such high levels of CO_2 have the potential to structure the fish community within the LCR, but little is known about CO_2 tolerances of humpback chub or other native Colorado River fishes. Measures of upper lethal CO_2 tolerances will be made in the laboratory for all fish species commonly found within the LCR and for invasive nonnative fishes that could become established within the LCR. Both adult and juvenile life stages will be evaluated. Captive reared humpback chub from the Southwestern Native Aquatic Research and Recovery Center in Dexter New Mexico will be utilized for these studies. All other species will be captured from the LCR in Grand Canyon.

Project Element 7.8. Evaluate effects of Asian tapeworm infestation on juvenile humpback chub

David Ward, Fishery Biologist, USGS/GCMRC

The objective of this project is to monitor the extent of Asian fish tapeworm (*Bothriocephalus acheilognathi*) infestation in juvenile humpback chub annually in the LCR and assess potential impacts to humpback chub populations. Asian fish tapeworm has been identified as one of six potential threats to the continued persistence of endangered humpback chub (USFWS 2002). It is potentially fatal to multiple age classes of fish (Schäpperclaus 1986), and has caused high mortality when infecting new host species (Hoffman and Schubert 1984). Asian fish tapeworm was first documented in the LCR in Grand Canyon in 1990 (Minckley 1996) and is hypothesized to be a cause of long-term declines in condition of adult humpback chub from the LCR (Meretsky and others 2000). The life cycle of Asian fish tapeworm is highly temperature dependent (Granth and Esch 1983) and management options aimed at increasing mainstem Colorado River water temperatures may permit Asian tapeworm to increase in number and range with detrimental effects to humpback chub. Monitoring is needed since no baseline information for tapeworm infestation in humpback chub is available. USFWS captures juvenile humpback chub from the LCR each summer prior to monsoon flooding for translocation into Grand Canyon tributary streams such as Shinumo Creek and Havasu Creek. These fish are held at the Southwest Native Aquatic Research and Recover Center (SNARRC) in Dexter, New Mexico prior to being PIT tagged and translocated. They are treated with Praziquantel to remove Asian Tapeworm as part of this process but no efforts have been made to quantify tapeworm loads in these fish. We propose to non-lethally quantify tapeworm loads (Ward 2007) on an annual basis from humpback chub collected for translocation. Our objectives are to establish a baseline of tapeworm infestation levels in LCR humpback chub and to determine whether year-to-year variation in the prevalence of tapeworm infestation is linked to annual variation in growth, survival or abundance of juvenile humpback chub.

Project Element 7.9. Development of a Non-Lethal Tool to Assess the Physiological Condition of Humpback Chub in the Colorado and Little Colorado Rivers

Kimberly Dibble, Research Biologist, USGS/GCMRC
Mike Yard, Fishery Biologist, USGS/GCMRC
David Ward, Fishery Biologist, USGS/GCMRC

This research focuses on laboratory work to test the feasibility of a more sensitive technique to assess the condition of native fish, which could then be used in the field as a non-lethal tool to monitor the health and condition of fish residing in mainstem aggregations and in the LCR. Past research studies using length-weight relationships and recapture data have observed differences in fish condition and growth between fish residing in the mainstem vs. the LCR. Findings have shown periodic and seasonal declines in adult humpback chub condition, where fish recovered more rapidly in the Colorado River than those remaining in the LCR (Meretsky and others 2000). Similar patterns have also been observed for juvenile humpback chub growth rates (Finch and others 2013; Hayes and others, unpublished data), findings that are of concern because of implications to humpback chub survival. However, these length/weight relationships may not provide an accurate assessment of the true physiological condition of fish because relationships change through ontogeny and seasonally (Bolger and Connolly 1989, Cone 1989, Simpkins and others 2003, Froese 2006), and weights may be overinflated due to ova (eggs), parasites, hydrated tissues (water gain following lipid loss), and/or instrument error, especially for small fish. Further, high summer growth of humpback chub in the LCR followed by low growth in early fall suggests that the energy allocation strategy of these fish shifts toward fat storage in preparation for winter rather than somatic growth (length or weight gain). Investment into lipid storage would increase the condition of humpback chub, but this is not reflected in growth analyses. Therefore, humpback chub monitoring of growth and condition would be improved through the development of a tool in the laboratory to assess the condition of native fish, which would eventually be incorporated into field monitoring efforts.

Bioelectrical Impedance Analysis (BIA) is a tool that has been successfully developed for cyprinids and other fish species (e.g., common carp (*Cyprinus carpio*), brook trout (*Salvelinus fontinalis*), cobia (*Rachycentron canadum*), steelhead (*Oncorhynchus mykiss*)) in both freshwater and marine ecosystems (Cox and Hartman 2005, Duncan and others 2007, Hanson and others 2010, Klefoth and others 2013); however, this technique has not been refined for native cyprinids such as humpback chub, roundtail chub (*Gila robusta*), or sucker species of interest in the Colorado River basin. BIA measures body condition and is based on the technology used by humans to estimate percentages of body fat and water when they step on an at-home digital scale. A low-level, safe, electrical current is passed through the human body (or fish body), and the level of "impedance" is measured. Fat offers more resistance to electrical current than water, so a human (or fish) that has a higher fat content will score higher on the impedance scale. For fish, a higher impedance reading correlates to better condition and indicates the fish is more likely to survive periods of low food availability, disease outbreaks, successfully reproduce the following spring, and cope with environmental perturbations.

The temperature of the water in which a fish resides can significantly influence BIA readings (Klefoth and others 2013), so we will develop a suite of experimental treatments in the laboratory where temperature and food rations can be controlled. Throughout each experiment, repeated measures of impedance in hatchery-raised humpback chub and/or surrogate species (e.g., roundtail chub, bonytail (*Gila elegans*)) of varying lengths will be quantified using a Quantum IV Body Composition Analyzer. Relationships between impedance readings and proximate body composition (percent lipid, protein, carbohydrate, water, ash) of sacrificed fish from laboratory experiments will allow us to calibrate the models for use in subsequent field monitoring (we need this calibration to verify the BIA analyzer is accurately characterizing the condition of native fish species). Since we need to develop these relationships for multiple species of varying lengths, this project will occur in several phases over 3 years to allow hatchery fish to grow to the size of comparable fish in the field.

Project Element 7.10. Humpback chub population modelling

Charles B. Yackulic, Research Statistician, USGS/GCMRC
Maria Dzul, Fishery Biologist, USGS/GCMRC

The ultimate objective of this project is to provide better tools to understand the current state of the humpback chub resource (i.e., adult population size) and to predict its future state in response to management decisions. In some instances, better prediction will come mainly through the incorporation of more data (e.g., additional JCM data will help determine whether trout and temperature relationships developed for the LTEMP model hold), whereas other instances require substantial intellectual investment into building appropriate statistical models (e.g., efforts to incorporate data collected through remote sensors (Project Element 7.4) with data collected through mark-recapture techniques (Project Elements 7.1-3)). One areas of emphasis in F2015-17 will be on better estimation of juvenile humpback chub production and outmigration, as well as on potential mechanisms that may explain year to year variation in these population processes. Another area of emphasis will be on further clarifying relationships between temperature, trout abundances and juvenile humpback chub population biology in the mainstem. Specific attention will be placed on publishing statistical models used to link temperature and rainbow trout analyses to humpback chub growth and survival for the LTEMP process as well as exploring the implications of these results for triggering management actions like mechanical removal of nonnative fishes. We can also envision modifying these models to jointly model rainbow trout abundance and humpback chub survival to provide more accurate estimates of uncertainty. A third area of emphasis will be on testing hypotheses about adult humpback chub capture probability and movement.

Project 8. Management Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon

A. Investigators

David Ward, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
William Persons, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Scott VanderKooi, Supervisory Biologist, USGS, Grand Canyon Monitoring and Research Center
Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
Clay Nelson, Fishery Biologist, NPS, Grand Canyon National Park
Emily Omana, Fishery Biologist, NPS, Grand Canyon National Park
David Rogowski, Fisheries Biologist, Arizona Game and Fish Department

B. Project Summary

This project encompasses two ongoing management actions and two new projects, all designed to increase survival of juvenile native fishes in Grand Canyon. In addition, we propose to convene a protocol evaluation panel comprised of external experts to conduct a review of the fisheries research, monitoring, and management actions conducted in support of the Glen Canyon Dam Adaptive Management Program (GCDAMP). In FY2015-17 we will continue ongoing mechanical removal of rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) using electrofishing near the confluence of Bright Angel creek, to reduce predation on juvenile native fish. We will also continue to translocate juvenile humpback chub (*Gila cypha*) annually from the Little Colorado River (LCR) into uninhabited areas within the LCR and continue to support translocation efforts into Havasu Creek and Shinumo Creek, to increase survival and distribution of humpback chub. In FY2016 or FY2017 we will participate in a review by external experts of these activities and other fisheries projects (see Projects 6, 7, and 9). The review of Project 8 activities will emphasize evaluation of the effectiveness of these management actions and the panelists will be asked to make recommendations as to whether the continuation of these efforts is warranted in future years. This project also includes two new project elements that will inform future potential management actions: 1). An assessment of invasive aquatic species within the LCR drainage, to evaluate potential risks to humpback chub populations and 2.) Genetic monitoring of humpback chub to confirm that ongoing management activities do not have detrimental effects on the genetics of the Grand Canyon population of this endangered species.

C. Proposed Work

C.1. Project Elements

Project Element 8.1. Efficacy and Ecological Impacts of Brown Trout Removal at Bright Angel Creek

David Ward, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Mike Yard, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Scott VanderKooi, Supervisory Biologist, USGS, Grand Canyon Monitoring and Research Center
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
Emily Omana, Fishery Biologist, NPS, Grand Canyon National Park
Clay Nelson, Fishery Biologist, NPS, Grand Canyon National Park

The objective of this project is to evaluate the feasibility and efficacy of brown trout removal in and around Bright Angel Creek using electrofishing, and assess the response of native fish to brown trout removal. A multi-year, brown trout removal treatment using mechanical removal began in 2013 and will be applied to the mainstem Colorado River and will complement ongoing NPS efforts in Bright Angel Creek with the objective of significantly reducing brown trout abundance by 75–80%. Removal in the Colorado River mainstem will occur in a 8.45 km (5.25 mile) reach of Upper Granite Gorge (river miles 85 to 90) using electrofishing depletion methods similar to those used from 2003 to 2006 at the confluence of the LCR (Coggins and others, 2011). Electrofishing removals on the mainstem Colorado River will occur during the fall-winter season and will compliment ongoing NPS operation of a weir and multi-pass depletions by backpack electrofisher within Bright Angel Creek from October to March. Efforts in the mainstem will consist of 6 to 10-pass depletions with a single pass occurring over the entire study area in two nights (amount of effort based on calculated capture probabilities with a goal of 75% reduction in brown trout numbers). It has been estimated that each trip will consist of 10-20 nights of sampling. All electrofishing will be conducted at night using two 16’ sport boats outfitted for electrofishing with a Coffelt® or equivalent CPS unit with one netter per boat. Large numbers of brown trout (> 2,000 fish) are likely to be removed. These fish will be put beneficial use as described in NPS’s Comprehensive Fish Management Plan (NPS 2013) and its associated Section 106 consultation with Native American tribes. To determine efficacy and ecological consequences of brown trout removal, capture probabilities for each study area will be estimated and used to develop a closed population model for estimating size-structured abundance of brown trout. Densities and conditions of native fishes will be monitored by NPS in Bright Angel Creek and by GCRMC in areas near its confluence. Continued native fish monitoring, both within the removal area and in other areas downstream, are needed to assess if increased dispersal of native fish is occurring as a result of removal efforts. This project was initiated in 2013-2014 (Nelson and others 2014) and we propose that this experimental management action be continued in FY2015 with possible extension through FY2017.

Project Element 8.2. Translocation and monitoring of Humpback chub above Chute Falls in the Little Colorado River

Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
D. R. VanHaverbeke, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
William Persons, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center

The objective of this project is to increase the survival of up to 1,000 juvenile humpback chub annually by translocating them from the lower LCR into areas above the Chute /Atomizer Falls complex in the LCR or into Shinumo Creek or Havasu Creeks. These locations all have low large-bodied fish densities and high food abundance (Robinson and others 1996, Spurgeon 2012), which would presumably lead to increased growth rates and higher likelihood of survival. In the December 2002 and November 2004 Biological Opinions on the proposed experimental releases from Glen Canyon Dam and removal of nonnative fish within the Colorado River, a conservation action was identified to relocate approximately 300 humpback chub (50-100 mm TL) in 2003 and 2004, and another 600 fish in 2005 from near the LCR confluence to an upstream LCR reach above Chute Falls that was previously unoccupied by this species. Additional translocations ensued following the recommendations of other Biological Opinions, whereby translocation and monitoring efforts of humpback chub in this upper portion of the LCR corridor have been incorporated as a conservation measure in the recent Final Biological Opinion on the Operation of Glen Canyon Dam Including High Flow Experiments and Non-Native Fish Control (U.S. Fish and Wildlife Service, 2011). Through 2013, 2,363 juvenile (50 -130 mm TL) humpback chub have been translocated upstream of Chute Falls (Stone and others in prep). From 2003 to 2013, 777 unique humpback chub (i.e., counted only once) have been captured above Chute Falls, of which 369 were adults (≥ 200 mm). Additionally, 1,540 unique humpback chub (893 were ≥ 200 mm) were captured directly downriver in the small 0.5 km Atomizer reach. The rapid growth rates of humpback chub in these two reaches resulted in many individuals losing their elastomer tags before they were recaptured, making it difficult to distinguish the original origin of many of these fish (i.e., translocated, progeny, or upriver migrants); however, all humpback chub translocated since 2008 have been PIT-tagged before being released, which is allowing much of this information to be recouped. From 2006 to 2009, two-pass mark recapture population estimates of humpback chub were conducted annually in the Atomizer reach and above Chute Falls, after which capture probabilities have been used to estimate the populations. Monitoring will continue to occur during the spring, prior to monsoon flooding to evaluate the retention and growth rates of translocated humpback chub.

Project Element 8.3.Glen Canyon Dam Adaptive Management Program Fisheries Research, Monitoring, and Management Actions Protocol Evaluation Panel

Scott VanderKooi, Supervisory Biologist, USGS, Grand Canyon Monitoring and Research Center
Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Brian Healy, Fishery Biologist, NPS, Grand Canyon National Park
David Rogowski, Fisheries Biologist, Arizona Game and Fish Department

An external review panel comprised of scientists with relevant expertise will be convened in either FY2016 or FY2017 to ensure that the quality and relevance of fisheries science being conducted by GCMRC and its cooperators is held to the highest of standards. This panel will conduct a review of all aspects of the GCRMC fisheries program described in Projects 6, 7, 8, and 9 of the FY2015-17 workplan. They will make recommendations regarding the scope and direction of the program as well as provide an evaluation and recommendations for future work with respect to the level of effort, study design, and relevance of individual research activities.

Project Element 8.4. Little Colorado River Invasive Aquatic Species Surveillance

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Dennis Stone, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
David Ward, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Bill Persons, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center

The objective of this project is to identify surveillance sites within the LCR upstream of Grand Canyon that can provide early detection and response for emerging deleterious invasive aquatic species within the LCR drainage. If invasive species deleterious to humpback chub are detected, we will develop and implement a rapid response plan. In Arizona, dozens of aquatic invasive species have been introduced (fish, mollusks, crustaceans), have expanded distributional ranges, and pose a growing threat to native aquatic species. The first line of defense for reducing the impact from invasive species is preventing their introduction and establishment. Multiple management agencies, notably state wildlife agencies, maintain active invasive species prevention programs. Even the best prevention efforts cannot stop all invasive species, and thus, early detection, rapid assessment and Rapid Response (EDRR) actions represent a critical second defense.

In Grand Canyon, the LCR is the largest tributary and primary spawning ground for humpback chub, however, the species is limited to the lower 15 km of the system (Douglas and Marsh 1996; Gorman and Stone 1999). The LCR encompasses a basin of about 8,100 m^2 in eastern Arizona and western New Mexico, with its perennial headwaters arising near Mt. Baldy, Arizona. Estimates of surface water supply and contemporary cultural depletions by the Arizona Department of Water Resources (1989, 1990, 1994) feed approximately 95 reservoirs and 3,700 stock tanks. Reservoirs and stock tanks are potential sources of invasive species and many can readily feed into the LCR or its tributaries. Large quantities of human derived debris in the LCR in Grand Canyon illustrate the connectivity of the river in Grand Canyon to upper portions of the watershed. Biological connectivity also exists based on the capture of red shiner (*Cyprinella lutrensis*), common carp (*Cyprinus carpio*), fathead minnow (*Pimephales promelas*), black bullhead (*Ameiurus melas*), and plains killifish (*Fundulus zebrinus*) at Grand Falls, all thought to have originated hundreds of kilometers upstream (Stone and others 2007). Conservation success of humpback chub in the LCR and Grand Canyon is vulnerable to incursion by invasive aquatic species from upstream.

A Reasonable and Prudent Alternative in the 1995 EIS was to protect humpback chub in the LCR by development of a LCR Management Plan (USBR 1995). A final draft of the plan was completed in 2008 (Valdez and Thomas 2009). This study will augment that plan by providing specific information and data concerning sources of non-native fish within the LCR basin. Surveillance sites will be assessed based on their likelihood to concentrate/harbor species, watershed/sub-watershed reference location, accessibility, ability to be sampled. From 6-12 sites will be sampled annually in May-June using passive (entanglement nets, hoop nets) and active (seines, electrofisher) gears as appropriate.

Project Element 8.5. Genetic monitoring of Humpback chub in Grand Canyon

Kirk Young, Fishery Biologist, USFWS, Arizona Fish and Wildlife Conservation Office Bill Persons, Fishery Biologist, USGS, Grand Canyon Monitoring and Research Center
Wade Wilson, Geneticist, USFWS, Southwest Native Aquatic Resources Research and Recovery Center

The objectives of this project are to monitor genetic changes in the Grand Canyon population of humpback chub that may result because of ongoing management activities such as translocations. Humpback chub management actions in the lower basin of the Colorado River include annual population monitoring, translocations to Shinumo Creek, Havasu Creek, and the Chute Falls area of the LCR. In 2008, a refuge population was started at the USFWS Southwest Native Aquatic Resources Research and Recovery Center (SNARRC). As a result of these ongoing management actions, a small set of fin clip samples (about 30 per reach in the LCR) were taken to establish baseline genetic data in the LCR. An initial assessment of the LCR samples indicated no biologically meaningful differences between Boulders, Coyote and Salt reaches, but sample sizes were low. An initial and provisional assessment of Chute Falls reach showed a significantly higher *Fst* value (increased homozygosity compared to other LCR reaches) which would suggest genetic variation between these groups. The source of this difference, however, is uncertain. It is possible that the difference was due to sample error (sample size 40), or it may have indicated breeding by a small number of adults above Chute Falls being reflected in increased homozygosity of the offspring (8.1.) generation. In any case, funding for analyzing the LCR tissue samples has never been procured, and further investigation into such anomalies would appear warranted. Although baseline genetics data for humpback chub in the LCR and other mainstem aggregations has been collected, the authors of these studies stated unequivocally that sample sizes were low and results should be interpreted cautiously (Douglas and Douglas 2007, 2010; Connie-Keeler Foster and Wade Wilson, pers. com.).

Douglas and Douglas (2007) addressed the genetics of mainstem Colorado River humpback chub aggregations in Grand Canyon, and many of the results from their report were published in Douglas and Douglas (2010). Based on a sample size of 234 fish collected from nine areas in Marble and Grand Canyons, Douglas and Douglas (2010) indicated that humpback chub from the LCR downstream were clearly connected by gene flow, and proposed downstream drift of larvae and juveniles as the scenario, with the LCR population being the primary source. Contribution from occasional local reproduction by mainstem aggregates could not be excluded. Based on excess homozygosity, Douglas and Douglas (2010) specifically stated local reproduction may be occasionally occurring at Middle Granite Gorge. To date, this is the only baseline genetics data that researchers have concerning mainstem aggregations of humpback chub in Grand Canyon. The sample sizes obtained by Douglas and Douglas (2007, 2010) were generally very small, ranging from 4-26 fish from all aggregations except the LCR (n = 77) and Middle Granite Gorge (n = 80). This led Douglas and Douglas (2010) to suggest cautionary interpretation of some of their results, and underscores the need for additional baseline data.

Fin clips from approximately 300 humpback chub will be collected annually for DNA extraction and microsatellite genotyping. Samples will be collected throughout the LCR as well as from translocated fish and from fish in each of the established mainstem aggregations. It is expected that establishing baseline data will take 2-3 years after which only periodic sampling (once every 3-5 years) would be required.

Project 9. Understanding the Factors Limiting the Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons

A. Investigators

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B. Project Summary

Over the past few decades, electrofishing and creel monitoring data collected by Arizona Game and Fish Department (AGFD) in Glen Canyon and Lees Ferry has shown that the rainbow trout (Oncorhynchus mykiss) fishery is characterized by three undesirable properties, including: (1) instability in population size that has led to decadal cycles of high and low fish abundance; (2) increased potential for negative interactions between rainbow trout and native fishes, especially the endangered humpback chub (Gila cypha), primarily due to rainbow trout population expansion downstream (Yard and others, 2011); and (3) an absence of the large rainbow trout that are highly valued by the angling community (Schmidt and others, 1998). Accordingly, much of the recent biological research conducted in Glen and Marble Canyons has focused on understanding factors that influence the size and health of the rainbow trout fishery (Korman and Campana, 2009; Anderson and others, 2012; Cross and others, 2013), as well as determining how Glen Canyon Dam operations and other factors may influence interactions between non-native trout and native species downriver (Yard and others, 2011; Korman and others, 2012; Melis and others, 2012). Research findings from the Natal Origins Project (see Project Element H.2 in the GCMRC FY2013-14 workplan) suggest that rainbow trout downriver primarily originate from the Lees Ferry reach (Korman and others, 2012), but what is unknown is why these drift-feeding fish migrate downriver into reaches where environmental factors (i.e., reduced underwater light due to intermittent periods of high turbidity) may influence their ability to effectively forage (Kennedy, unpublished data). Another unknown is why local reproduction does not occur more frequently in Marble Canyon as it does in Glen Canyon (Korman and others, 2012). Physiologically, fish that exhibit reduced foraging capacity given physical parameters in the water column and/or prey size and availability will often not be able to successfully spawn since gamete development is energetically costly (Hutchings, 1994; Hutchings and others, 1999). For the FY2015-17 workplan, we developed a suite of research and monitoring projects that will elucidate some of the mechanisms behind changes in trout abundance, survival, movement, reproduction, and growth in Glen and Marble Canyons. These research efforts will provide information that can be used to better understand the potential for negative interactions between non-native trout and native species like humpback chub, and perhaps identify experimental treatment options for mitigating high rainbow trout abundance downstream of Lees Ferry.

Since the early 1990's AGFD has monitored the Lees Ferry rainbow trout fishery via electrofishing in multiple seasons, providing data that has fostered the development of research projects to investigate causal mechanisms behind changes in population and trout size over time. These data have been used to develop catch per unit effort (CPUE) indices as a surrogate for population size, but other research and monitoring programs have commenced that estimate population size via more robust mark-recapture methods. To reduce redundancy between programs and optimize the utility of data generated (e.g., mark-recapture population estimates in lieu of CPUE), the Natal Origins (*Project Element 9.2*) and Lees Ferry Rainbow Trout Monitoring (*Project Element 9.1*) projects have been partially consolidated in the FY2015-17 workplan. Monitoring of juvenile trout will continue under the Rainbow Trout Early Life Stage Survival (RTELSS) project, while creel data will continue to be collected by AGFD. Collectively, these monitoring data are essential to the management of the Lees Ferry trout fishery because they provide an indication of the influence of Glen Canyon Dam operations and other naturally occurring disturbances in the Colorado River ecosystem (CRe) on the health of the rainbow trout fishery.

In addition to monitoring adult and juvenile rainbow trout populations, a suite of new research activities will improve our understanding of the mechanisms that drive rainbow trout population dynamics as they relate to dam operations and flow management actions. Specifically, these research projects will target questions related to characteristics of the physical habitat (e.g., channel-bed texture, water temperature, turbidity, water depth, and flow) and food base that may limit trout growth, size, and reproduction including: (a) a quantification of the energy (lipid) reserves of drift-feeding trout in Glen and Marble Canyons to examine potential drivers of trout growth, movement, survival, and reproduction under varying light intensities pre- and post-monsoon; (b) a morphometric analysis of feeding structures in drift feeding fish to assess whether feeding efficiency is constrained by the size of invertebrate prey in the CRe; (c) a meta-analysis of data on the effects of light intensity, prey size, predator size, and turbidity on visual reactive distances of drift feeding fish, which will be used to develop an encounter rate model that predicts how light intensity and prey size affects trout foraging success and growth in Glen and Marble Canyons; (d) a laboratory study to assess the feasibility of using dam operations following fine sediment inputs (sub-sand sized) into Marble Canyon so as to assess whether or not managing turbidity is feasible as a trout management tool during minimum-volume dam release years; (e) development of bioenergetics models to quantify the effects of turbidity and food availability on trout growth in Marble Canyon; (f) an assessment of the mechanisms that limit trout growth in other tailwaters using data collected during the tailwater synthesis project; (g) development of population dynamic models that assess growth, reproduction and movement of rainbow trout between Glen and Marble Canyons; and (h) an evaluation of the effects of fall High Flow Experiments (HFE) on the growth, survival, movement, and condition of young-of-the-year rainbow trout via comparison of data from HFE and non-HFE sampling years. Collectively, results from these monitoring and research projects will be used to identify key drivers behind changes in rainbow trout population size, movement, survival, reproduction, size, and condition that will be used to better manage the trout fishery while protecting endangered fish populations in the CRe.

C. Proposed Work- Monitoring and Research Projects

C.1. Project Elements- Research

Project Element 9.1. Lees Ferry Rainbow Trout; Monitoring, Analysis, and Study Design

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William Persons, Fishery Biologist, USGS, GCMRC
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The objectives of this monitoring project and several related project elements are to: (1) reduce sampling redundancy in Glen Canyon and Marble Canyon rainbow trout monitoring (FY2015-2016); (2) transition the Juvenile Chub Monitoring project (*see project element 7.2*) from a research focus to a monitoring effort conducted collaboratively by GCMRC and its cooperators; (3) transition the System Wide Electro-Fishing (SWEF) project (*see project element 6.4*) from a sampling approach based on catch rate indices to one that also estimates fish abundance and vital rates (FY 2015-2016); (4) convene an independent protocol evaluation panel (PEP) in late FY 2016 or early FY 2017 to review the GCDAMP fisheries program (*see project element 8.3)* ; and (5) review and implement as appropriate PEP recommendations as a collaborative effort between GCMRC and its cooperators (FY 2017).

To date, rainbow trout monitoring in Lees Ferry and the SWEF project (*see project element 6.4*) have been effective in sampling and assessing status and trends for most of the adult fish community (Makinster and others 2010). We believe, however, that catch rates are now inadequate for meeting current management information requirements. In comparison, other studies using sampling approaches where mark-recapture data are collected and analyzed with multiple modeling techniques have been shown to be very practical for monitoring the status (actual abundance and occupancy) and vital rates (survival, growth, and movement) for both native and nonnative fishes (Speas and others 2004; Coggins 2011; Yackulic and others 2013; VanHaverbeke and others 2013; Korman and others unpublished data). The ongoing Natal Origin Research project (*see project element 9.2*) provides an effective sampling approach for collecting and analyzing mark-recapture data for estimating rainbow trout abundances in five reaches found in Glen and Marble Canyons, as well as below the LCR.

Although the primary objective of this project is to better understand factors influencing trout demography, these same data are also being used to inform triggering criteria for nonnative fish control measures (USDOI 2011_a) and for modeling alternatives for the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) (USDOI 2011_b). Because of this there is considerable sampling redundancy occurring between the current Natal Origin Research project and the Lees Ferry Rainbow Trout Monitoring program. Nevertheless, the Natal Origin Research project is scheduled to be completed by the end of FY-2016, which leaves a significant data gap in outlying years required by management downstream of the LCR (*see 7.2*). Therefore, the sampling methodology for long-term fish monitoring needs to be redesigned and implemented after the conclusion of this study. In the interim, a transitional sampling approach in needed to provide the necessary fishery data for the FY2015-17 workplan and sets the stage for outlying years.

To avoid sampling redundancy, we propose that the SWEF project (*see project element 6.4*) discontinue standard sampling (single-pass) in the Glen Canyon and Marble Canyon reaches until the beginning of FY-2017. Instead, we propose that mark recapture sampling be conducted at sites located between the established Natal Origin Research project study reaches to estimate intermediate movement distances occurring among tagged trout found between reaches not currently sampled. In addition, GCMRC in conjunction with Ecometric Research, Inc., and AGFD will use existing mark-recapture data to develop a set of estimation procedures for conducting simulations to redesign the sampling design inclusive of the Lees Ferry Rainbow Trout Monitoring and SWEF programs. Upon completion, we propose that the independent PEP (*see project element 8.4*) evaluate the prospective monitoring objectives, sampling design, and analytical methods. Results from this independent review process will help GCMRC and its cooperators design a new sampling program to monitor the Glen Canyon fishery as well as the downstream reaches from the Paria River to Pearce Ferry.

In cooperation with GCMRC, AGFD will jointly share in the data collection activities in FY-2017 to continue the management requirements specified in the USFWS Biological Opinion (USDOI 2011_a). In order to make this a seamless transition, AGFD personnel are to actively participate on each of the quarterly Natal Origin Research project trips during 2015-2016 so as to become familiar with the Juvenile Chub Monitoring (JCM) project.

Project Element 9.2. Detection of Rainbow Trout Movement from the Upper Reaches of the Colorado River below Glen Canyon Dam/Natal Origins

Josh Korman, Ecometric Research, Inc.
Michael Yard, Fishery Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The central objectives of this research project are to (1) determine the natal origins of rainbow trout in the Marble Canyon/LCR confluence area via a large-scale mark and recovery effort, (2) to evaluate the linkage between trout populations in the Lees Ferry reach and Marble Canyon, (3) assess the efficacy of the proposed alternative of a trout removal effort between the Paria River to Badger Rapid (PBR), (4) develop analytical methods for monitoring abundance, survival, recruitment and capture probability of rainbow trout in the CRe. And lastly (5) studying the response of juvenile native fish to changes in trout density near the LCR area resulting from removal and experimental flow treatments will be used to support the data and analytical requirements as per the Biological Opinion ($USDOI_a$ 2011) (*see project element 7.2* [*Juvenile chub monitoring*]).

This project as originally described in the FY2011-2012 Work Plan (BIO 2.E18.11, 12), has been modified and expanded (*see FY2013-14 Work Plan*) with fieldwork continuing through the end of FY2016. The scheduled completion for this project is 1st quarter of FY2017. This study is a research project to determine if Glen Canyon is the natal source of trout emigrating into the downstream reaches of Marble and Grand Canyons (Korman and others, 2011). Information from this project will help resolve some of the uncertainties about prescribing nonnative fish control activities such as fish suppression flows (e.g., LTEMP possible alternatives), or in locations that are geographically distant to the area of concern (Little Colorado River confluence area). This project is based on existing information (Coggins, 2008; Korman and others, 2012) that concludes that rainbow trout reared in the Lees Ferry reach of the Colorado River (Glen Canyon Dam to Lees Ferry) move downstream under some conditions.

The analytical methods being developed to assess trout movement use a robust-design (RD, 2 km section) where captured fish are spatially referenced at a 250 m resolution in all sampling reaches (Lees Ferry [R1], House Rock [R2], Buckfarm [R3], Above LCR [R4], and Below LCR [R5]) on initially on pass 1, and when recaptured on pass 2 or on other sampling trips. Therefore, emigration losses can be determined based on observations of movement distances of fish released in the RD section and subsequently recaptured at the same or different locations within or across trips. To further supplement this movement information, 2 km sections upstream and downstream of the RD section in reaches R1-3 are sampled. This spatial layout allows us to detect within-reach movements of up to 4 km, but the opportunity to detect shorter movements is greater than for larger ones. Fitting parametric distributions to such data facilitates comparison of movement patterns among reaches and trip intervals, and can also be used to derive a robust estimate of emigration losses for an open population modeling approach like the Jolly Seber (JS) model. Although, the current sampling design allows for estimations of trout movement distances occurring within and across sampling reaches located between Glen Canyon and the LCR; the spatially fixed sampling approach (5-reaches) limits estimations of intermediate movement occurring among tagged trout found between reaches that are not currently sampled. To acquire additional trout movement data for between reach movements of tagged animals, AGFD is planning on conducting mark recapture studies between the five sampling reaches in Marble and Eastern Grand Canyons during FY2015-2016 (*see project element 6.4).*

The JS model is used to estimate reach-specific abundance, survival and recruitment based on data from the RD mark-recapture sampling design. The apparent survival of marked fish in RD sections based on the decline in recaptures of each marked cohort (a group of fish released in a reach on a given trip) through time. That decline depends on mortality rate as well as loss of fish due to emigration from RD sections. Estimates of movement are required to convert the apparent survival normally estimated by a JS model (which includes losses from mortality and movement) into an actual survival rate, by comparing models where survival rate can vary among trips vs. models where survival is assumed to be constant. Using different modeling approaches allows for estimating abundance at the start of each trip, survival and recruitment between trips, and capture probability for each trip and pass. Parameters of the different models are estimated by minimizing the negative value of the total log likelihood and using the nonlinear search procedure in the AD model-builder (ADMB) software (Fournier et al. 2011). Abundance of unmarked fish at the start of the 1st pass on trips 2 and later depends on abundance at the end of the last pass on the previous trip, and survival and recruitment between trips. Combinations of models (Mt-So, Mtb-So, Mt-S*, Mtb-S*) are being evaluated using Akaike's Information Criteria (AIC, Burnham and Anderson 2002). Model selection, particularly the use of Mb model (behavioral response to capture) types are required because of detection differences for within trip vs across trip. This is likely due to spatial heterogeneity that leads to overestimating capture probabilities and results in an underestimation of trout abundance. These habitat linked differences in fish vulnerability to capture might arise due to fish moving to lower velocity or more protected/shallow habitats, and are to be addressed by some additional habitat assessment (*see project element 10.1*).

Preliminary results from this research study (GCMRC Annual Reporting Meeting, January 2013 & 2014); indicate relatively modest movement of trout between trips with a high proportion of recaptures found in their original release sections, or in adjacent sections, and the vast majority of the recaptures occurring within a 2 km of the original release locations. To date, movement rates into a reach (immigration) rather than out of a reach (emigration) have been considerably less (1/2 the rate observed in 2003) than those reported for previous studies (Coggins 2008; and Coggins and others, 2011) near the LCR. This suggests that the current low immigration rate for trout may be indicative of relatively good conditions for growth in Marble Canyon which could reduce downstream dispersal (*see project elements 9.3-5, & 9.9*), and that movement is more episodic rather than incrementally constant. This is the underlying rationale for such an extended research project (2012-2016). Trout growth is key to interpreting the observed differences in length frequencies and provides the insight on the underlying mechanisms for trout movement. Trout growth is very limited between Sep-Jan and likely most of Jan-Apr period and may be linked to low food availability (*hypothesis **H2***) or low feeding efficiency (***H2.1-3***). The differential trout growth as observed among the five RD sections provides insight on understanding what fraction of the Marble Canyon fish immigrate into the LCR inflow reach.

This research project also provides the logistical framework to support the fieldwork necessary for a number of other study projects, these include several project elements in Project 9 “Understanding the Factors Limiting the Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons”, project element 7.2., “Mainstem monitoring of native and nonnative fishes near the LCR confluence -Juvenile Chub Monitoring” (as per USDOI$_a$ 2011), and Project Element 5.2. “Linking invertebrate drift with fish feeding habits.” Owing to the extensive tagging effort in this study, other research studies are possible which allow for greater collaboration between these research studies. Currently the NO project provides the logistical framework for data collection and some of the analysis as part of the JCM project (*see Project Element 7.2*) and other research elements proposed addressing the underlying mechanisms for trout growth and possible movement (*see Study Elements: 5.2.2, 9.2, 9.3, 9.4, 9.7, 9.9, and 9.10*).

Products expected from this project are a series of peer-reviewed publications.

Project Element 9.3. Exploring the Mechanisms behind Trout Growth, Reproduction, and Movement in Glen and Marble Canyon using Lipid (fat) Reserves as an Indicator of Physiological Condition

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Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research Inc.
Ted Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The objective of this research is to determine whether the ability of adult rainbow trout to acquire and store energy from the prey base is a potential mechanism behind spatial and temporal differences in growth, reproduction, and movement of rainbow trout in Glen and Marble Canyons.

As described in GCMRC's FY2013-14 Work Plan (*see Project Elements 9.2 & 7.2.2*), rainbow trout size, distribution, diet, and prey base data have been collected for the past two years to examine potential drivers of trout growth, movement, and population size in Glen and Marble Canyons. Continuations of these projects have been requested as part of the FY2015-17 Work Plan (*see Project Element 9.2*), so we propose to add an additional component to this project to quantify lipid (fat) reserves in a subsample of the fish that are already sacrificed to collect data on trout diet. This provides an opportunity to leverage an existing project to gain exciting scientific information in a cost-effective way. Briefly, five sampling reaches downstream from Glen Canyon Dam will be sampled on two separate nights during four seasons over one year. Fish tissue (muscle, liver, hindgut) will be excised, preserved in liquid nitrogen, and brought back to GCMRC for biochemical analysis. In the laboratory, total lipid will be extracted gravimetrically (Bligh and Dyer 1959, as modified by Phillips and others, 1997) and then separated into lipid classes (e.g., non-polar "storage" lipids and polar "structural" lipids) using high-performance thin layer chromatography (Churchward and others, 2008; Zhou and others, 2012). These data will then be used to: 1) examine temporal and spatial differences in the physiological condition of trout in Glen and Marble Canyons; 2) improve rainbow trout growth models currently in development by Korman and Yard; and 3) understand the mechanisms behind the maximum size and growth potential of rainbow trout in Lees Ferry.

Lipid mass data will be examined in combination with growth (mark-recapture data from the whole population; *Project Element 9.1*), diet (from the same individuals), and drift availability (*see GCMRC's FY2013-14 Workplan, Project Element F.7.1, FY2015-17 Workplan, Project Element 5.2.2)* to assess how energy availability and storage plays a role in rainbow trout growth, reproduction, and movement across all study reaches during multiple seasons. These data will be especially important in elucidating the mechanisms behind reproduction in Marble Canyon. If adult rainbow trout are critically depleted in lipid mass throughout the growing season (e.g., due to high turbidity in summer) such that energy stores are depleted in fall and spring, there is a high likelihood that fish in Marble Canyon may choose to forgo spawning or reabsorb eggs and gametes to survive (Adams 1999, Hutchings and others, 1994, 1999), which may explain the apparent reduction in local reproduction in lower Marble Canyon by the LCR (Korman and others, 2012).

These data will also be used to improve modeling efforts that assess rainbow trout population dynamics in Glen and Marble Canyons. Korman and Yard have analyzed preliminary data from the Natal Origins project to assess spatial and temporal differences in rainbow trout growth (length and weight; GCMRC Annual Reporting Meeting, January 2014; http://www.usbr.gov/uc/rm/amp/twg/mtgs/14jan30/). However, unexplained patterns in weight loss in the late summer (when the fish should be gaining weight in preparation for winter) indicate the fish may have switched to a fat storage strategy (Adams 1999), which as described above, would be under-represented in the growth analysis. Models will be improved by incorporating data on spatial and temporal fluctuations in tissue energy density, which is a more reliable indicator of weight gain.

In addition to helping answer mechanistic questions related to rainbow trout growth, these data will also improve our understanding of factors that constrain the maximum size of trout in Lees Ferry. One of the main hypotheses in the FY2015-17 Work Plan (**H.2**) was that the size of and species available in the prey base (primarily midges and black flies) support the growth of small rainbow trout but limit the growth of large adult trout. This hypothesis is supported by research conducted by McKinney and Speas (2001) that found that adult rainbow trout are more often food-limited than smaller trout. Rainbow trout, like other temperate fishes, invest in somatic growth (length) prior to investing in visceral (fat) stores, so lipid mass vs. length should show an allometric relationship (Post and Parkinson, 2001; Simpkins and others, 2003). However, preliminary data indicate the opposite, with small fish having larger fat reserves per gram of body tissue than large adult fish (Dibble, unpublished data). Therefore, additional lipid data will be very useful in evaluating the hypothesis that rainbow trout fail to reach trophy status due to a diminished prey base.

Project Element 9.4. Comparative study on the feeding morphology of drift feeding fish

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Joel Sankey, Research Physical Scientist, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Josh Korman, President, Ecometric Research Inc.

The objective to this project element is to determine if prey retention efficiencies associated with the feeding morphology of rainbow trout, brown trout, and humpback chub are potentially constrained by the size of invertebrate prey available in the CRe.

Prey size has a strong effect on foraging success because prey items are not always retained once consumed. In a functional sense, once prey items are captured in the mouth cavity of a fish, water passes through the gill-rakers like a sieve, and prey are retained and ingested. Therefore, branchial arch/gill-raker morphology may control feeding efficiencies (i.e., the number of prey consumed divided by the number of prey captured) such that larger prey items are more often retained than smaller prey. Feeding efficiencies change because morphological structures become larger with increasing fish length (Breck and Gitter, 1983; MacNeill and Brandt, 1990), which cause larger fish to selectively retain only larger prey items (Budy and others, 2005). Therefore, size-related changes in feeding morphology are likely to vary within the same species due to plasticity of morphological traits (Keeley and others, 2007); essentially structural relationships may vary between different environments even though it is the same species. Similarly, these same morphological structures are highly likely to vary among different species, which may be partially responsible for resource partitioning. Lack of prey diversity and minimal prey size in the CRe (Cross and others, 2013) has likely influenced competitive and piscivorous interactions between native and non-native fishes. Findings from these analyses will be used to test hypotheses **H2.1**, **H2.2**, and **H3** (potential for intra- and interspecific competition)

In this study, we propose to (1) measure gill-raker number, length, and spacing for three drift feeding species: rainbow trout, brown trout, and humpback chub; (2) develop and compare branchial arch and gill-raker morphology within and among fishes; (3) determine if mean prey size distributions found in fish diet correlate with morphometrics (i.e., method of quantifying a structure through measurements of size, shape, and quantity); (4) determine if diet electivity for prey size distributions are proportionally greater in the fish diet than what is found available in the drift, and (5) evaluate different methods (conventional ocular microscopy, photometric analysis [hand- or computer-traced outlines], and automated – photometric analysis [smart algorithms]) used for measuring and enumerating anatomical structures. Exploring these other types of quantitative methods may further reduce the amount of analytical time and cost associated with conducting these types of morphometric measurements.

Invertebrate drift and diet samples for rainbow and brown trout have been and are continuing to be collected as part of the Foodbase Monitoring project (*see GCMRC's FY2013-14 Workplan,* *Project Element F.7.1*). Since humpback chub are an endangered species, source material used for morphometric analysis will be acquired from incidental mortalities (GCMRC monitoring program, 2000-Present), archival collections, and from breeding stock mortalities at Dexter National Fish Hatchery. For each fish species, we will evaluate a large size distribution (~50 to 400+ mm fork length) and develop relationships between fish size and morphological characteristics. The minimum fish size has yet to be determined because of developmental differences in feeding structures. For comparative purposes, morphological data will be paired with detailed diet analysis (prey size and prey densities), using a subset of fish samples containing both branchial arches and stomach contents. For the fish length relationships we will select and measure three fish per size class, with samples grouped at 5 mm increments. Because of limited availability, comparisons made between chub diet and feeding morphology are unlikely. This project will produce two manuscripts, each suitable for publication. Expected timeline for project completion is 2017.

Project Element 9.5. Meta-analysis, and the development of reactive distance relationships for encounter rate models

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Josh Korman, President, Ecometric Research Inc.
Charles Yackulic, Research Statistician, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC

The objective of this project element contains two parts: (1) determine the effects of varying light intensity and prey size on fish reactive distances; and (2) develop an encounter rate model for drift feeding fish that accounts for varying reactive distances and prey availability within the range of channel depths and light levels encountered in Glen and Marble Canyons.

Underwater light intensities are likely to interact with different prey sizes because larger rather than smaller items are perceived at greater distances. Reactive distance relationships have been developed for a number of fish species (e.g., Howick and Obrien, 1983; Vinyard and O'Brien, 1976; Ware, 1973); however, inconsistencies exist in the literature. This is partly due to the scope and range of variables experimentally tested, particularly with the use of turbidity as a predictive proxy for light (e.g., Barrett and others, 1992; Sweka and Hartman, 2003). Considering that underwater light intensities change over the day and with increasing depth, most turbidity-based relationships are limited in application to small, clear, and shallow (depth < 0.5 m) streams. There are however a number of existing models that have been developed specifically for the CRe that account for variation in light reaching the water surface due to canyon topography (Yard and others, 2005) as well as predictive relationships between the underwater light attenuation and suspended sediment (Yard, 2003).

We will conduct an extensive meta-analysis on all known published data on reactive distances (i.e., distance a prey item can be visually detected) of visual sight-feeding fish. We will evaluate literature and quantitatively summarize regression slopes obtained from independent studies, either published as relationships or through extraction of data from graphs and tables (Tummers, 2006). Through this meta-analysis we are going to refine the predictive capabilities of these reactive distance relationships so that they can be broadly applied to more realistic environmental conditions. We will evaluate specific variables that affect predator reactive distances, including light intensity, turbidity, prey size, and predator size. Findings from this data synthesis will inform the process used in selecting or developing the most appropriate relationships to use in developing an encounter rate model (i.e., quantifying the daily number of drifting invertebrates encountered by a visual sight feeding fish; Gerritsen and Strickler, 1977; Harvey and Nakamoto, 2013).

Data sets from both long-term monitoring and research studies will be used for developing an encounter rate model for rainbow trout. These data requirements include seasonal variation in invertebrate drift (*Project Element 5.2.2*), and other physical data such as instantaneous light intensities (Yard and others, 2005), channel characteristics, flow discharge, and suspended sediment concentrations (http://www.gcmrc.gov/discharge_qw_sediment/). Encounter rates will be determined for five specific study reaches (NO reach designation) located between Glen Canyon and the LCR confluence area. We will model the potential influence that reduced light levels have on the frequency of trout daily encounter rates (mediated through differences in channel depths, turbidity levels, and invertebrate drift). Findings from these analyses will be used to test hypothesis **H2.3**, as well as compare responses to other independent data on trout diet (*see project element 5.2.2.*), monthly growth rates (*see project element H.2*), and physiological condition (*see project element 9.3*). Results from this will determine whether or not reduced encounter rates exert a population-level effect on rainbow trout throughout Glen and Marble Canyons. This project will produce two manuscripts, each suitable for publication. Expected timeline for project completion is 2017.

Project Element 9.6. Evaluation of Turbidity (in terms of TSS) as a potential Glen Canyon Dam operations management tool to constrain rainbow trout populations and reduce predation/competition on juvenile humpback chub

David Ward, Fishery Biologist, USGS, GCMRC

The objective to this project element is to determine what level and duration of turbidity would be necessary to negatively effect, or prevent persistence of, rainbow trout in the areas near mid-to-lower Marble Canyons and below the Little Colorado River confluence in eastern Grand Canyon. This project also aims to determine whether turbidity levels in the Colorado River could be manipulated during years of minimum annual release coincident with Paria and Little Colorado River fine-sediment inputs, so as to limit downstream rainbow trout outmigration from their natal origin habitat areas above the Paria River.

Predation on juvenile humpback chub by rainbow trout is considered a significant threat to humpback chub populations in Grand Canyon (Marsh and Douglas, 1997; Coggins and others, 2011; Yard and others, 2011; Runge and others, 2011). Relatively low levels of turbidity <100 Formazin Nephelometric Units (FNU) have been found to effectively reduce vulnerability of juvenile humpback chub to predation by rainbow trout (Ward, 2014 AMWG poster session, unpublished data), and extended periods of turbidity have been shown to negatively impact and exclude salmonids in other systems (Harvey and Railsback, 2011, reviewed in Newcombe and MacDonald, 1991). Increasing turbidity can also have positive effects on small species and juvenile fish but a negative effect on larger piscivorous fishes (Utne-Palm, 2002). Understanding how the magnitude and duration of turbidity in the Colorado River impacts various life stages of rainbow trout will allow researchers to better evaluate turbidity as a potential management tool of juvenile humpback chub in Marble and eastern Grand Canyons.

This project is intended to evaluate the feasibility of using dam operations in response to naturally input fine sediment-induced turbidity as a management tool to disadvantage trout populations in the mainstem Colorado River near the confluence with the Little Colorado River. This project includes laboratory studies to evaluate turbidity effects on trout, as well as modeling of turbidity (silt/clay) routing from the Paria River to areas downstream of the Little Colorado

River down to river mile 87 (Grand Canyon stream gage near Phantom Ranch). In the laboratory, we will evaluate the effects of multiple turbidity concentrations (50 – 200 FNU) and extended high turbidity durations (1-5 months) to identify turbidity thresholds that negatively impact rainbow trout and reduce survival. LISST-100 instrumentation will be used in combination with YSI turbidity probes to compare level of FNUs to total suspended sediment concentration and grain size distributions in controlled tank experiments (Voichick and Topping, written commun., USGS, 2014). We propose to develop a model (Anderson and Wright, 2007) to include routing of sediment finer than sand; particle sizes which are known to significantly elevate turbidity at relatively low concentrations. This will enable researchers to route and predict the downstream fate of silt and clay (persistence of suspended finer sediments) that cause turbidity from the Paria River downstream into Marble and Grand Canyon, as well as between the LCR and Grand Canyon gage, so as to estimate the possibilities for routing silt and clay concentrations needed to produce target turbidities (determined from laboratory studies to disadvantage trout) upstream and below at the LCR confluence. This information will allow for science based, data driven discussions of possible annual-to-multiyear scenarios for seasonal dam operations under minimum annual release volumes from Lake Powell that may allow levels of turbidity associated with natural tributary sediment inputs to be used as a fish management tool.

Originally an idea from the 1995 EIS, MLFF was purposefully intended to allow accumulation of sand inputs within reaches below the Paria and Little Colorado Rivers prior to sandbar building controlled floods, but higher monthly release volumes associated with hydropeaking operations in winter and summer seasons have been shown to accumulate sand inputs under minimum volume release years when tributary sediment loads are above average and occur in consecutive years, such as Topping and others (2010) report for sediment years 2006-7, preceding the 2008 HFE. To date, evaluation of turbidity has been limited to field measurements in Marble Canyon during 2013-14; a period of above average Paria River sediment loading, the lowest annual release volume since 1964, but also a period of fall HFE operations. Flow and finer-sediment modeling would allow evaluation of the potential for season-to-season management of fines for elevating turbidity, but without having to forego fall HFEs after tributary sand enrichment as a large-scale experiment.

Understanding how turbidity impacts rainbow trout is critical in evaluating flow and exotic fish control management options aimed at preservation of native fishes in Grand Canyon. Runge and others (2011) in assessing 19 options for mitigating the negative influence of rainbow trout on humpback chub identified sediment augmentation from sources in Lake Powell to Lees Ferry as likely the most effective treatment for reducing trout predation on chub juveniles, and numerous studies (Reviewed in Newcombe and MacDonald, 1991) demonstrate that relatively low sediment concentrations can adversely impact rainbow trout populations. Questions regarding effects of turbidity on fish are difficult to answer in a field setting because of confounding factors and the often extended time periods needed to evaluate turbidity effects, but these types of interactions can often effectively be evaluated in laboratory settings (Hairston, 1989). Previous discussions about sediment augmentation below Glen Canyon Dam were aimed at restoring both sand and finer sediment to the river to benefit native fish, as well as sandbars, which was cost prohibitive, but small scale silt and clay augmentation that only increase turbidity slightly may be just as effective at reducing predation mortality of native fish and was identified by Randle and others (2007) as much less costly than sand augmentation. We currently have a very good 1-D sand routing model (Wright and others, 2010), but unfortunately sand has very little influence on turbidity (Voichick and Topping, written commun., USGS, 2014). Hence, additional modeling development is needed to route the finer sediments that cause turbidity. Seasonally focused flow management efforts to increase turbidity within the Colorado River may be a much more cost effective and acceptable solution than downstream mechanical trout removal (Coggins and others, 2011) as a means to reduce predation and competition on juvenile humpback chub, particularly during periods when dam releases are naturally warmer at the LCR; a condition known in 2011 to be associated with reduced juvenile chub annual survival (possibly, linked to increase trout metabolism; see Keiffer and others, 1994). This project will allow an assessment of turbidity as a trout management tool, from both a lab experimental perspective and in the context of field data and flow and suspended sediment modeling simulations tied to dam operations and tributary fine sediment inputs.

Project Element 9.7. Application of a bioenergetics model in a seasonally turbid river

Michael Dodrill, Fishery Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.

The objective to this project element is to adapt process-oriented ecological models (such as drift-foraging bioenergetics or net energy intake methods) to quantify the effects of physical conditions (i.e., flow, turbidity, and depth) and food availability on rainbow trout growth and distribution.

Understanding the linkages between food availability and growth of drift feeding fish in large regulated rivers presents significant challenges to scientists and managers. Process-oriented ecological models show promise for describing ecological dynamics in rivers across levels of biological organization (Anderson and others, 2006). Linked foraging-bioenergetics or Net Energy Intake (NEI) models explicitly consider physical habitat (depth, velocity) and ecological processes (drift-availability) to describe the foraging process and how food availability translates into fish growth. These methods have been used to assess the effects of invertebrate drift size structure on the lifetime growth of drift-feeding fish (Hayes and others, 2000), assess habitat, and provide an alternative to traditional approaches (i.e., PHABSIM) for predicting the response of fish changes in physical conditions, such as altered flow regimes (Rosenfeld and Ptolemy, 2012) or turbidity levels (Harvey and Railsback, 2009).

Building on preliminary methods developed for Lees Ferry (Dodrill, unpublished data), coupled drift-foraging bioenergetics have identified linkages between drift-availability and metabolic demands thought to limit overall fish growth. Benthic invertebrates are the ultimate source of drift consumed by rainbow trout and contribute to the spatial patterns of drifting invertebrates. Understanding factors that influence the spatial and temporal dynamics of invertebrate drift and physical factors (such as turbidity or flow conditions) that influence the detection of food items (*Project Element 9.5*) will help to correlate patterns of rainbow trout growth and abundance (*Project Element 9.2*) to underlying mechanisms. We propose integrating data sourced from existing and proposed projects to develop and parameterize process-oriented models. This includes information on invertebrate drift rates (*Project Element 5.2.2*), channel characteristics (*Project Element 10.1*), turbidity, and temperatures for river segments extending from Lees Ferry to the LCR.

Project Element 9.8. Mechanisms that Limit Rainbow and Brown Trout Growth in other Western Tailwater Systems

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Charles Yackulic, Research Statistician, USGS, GCMRC
Ted Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Phaedra Budy, Research Aquatic Ecologist, USGS, Utah Coop. Fish and Wildlife Research Unit
Michael Dodrill, Fishery Biologist, USGS, GCMRC

The objective of this research is to continue to develop a broader understanding of the links between dam operations and salmonid population dynamics by synthesizing data from tailwaters across the Western United States.

Under Project H.2 of GCMRC's FY2013-14 Workplan, the principal investigator amassed fishery, discharge, reservoir, food base, and other data from 56 dams throughout the West. We are in the process of analyzing this dataset and continued funding will maximize the degree to which the GCDAMP can learn from other tailwater ecosystems. The analysis presented at GCMRC's Annual Reporting Meeting (January 2014) was an appropriate first step at synthesizing these data and addressed one of the four main hypotheses (**H4**) related to changes in trout size over time relative to dam operations. This analysis focused on the influence of hydropeaking, seasonal flow, specific discharge, and other metrics on trout size, recruitment, and catch-per-unit-effort downriver of dams with multiple purposes (e.g., hydropower, irrigation, and storage). This analysis allowed us to understand broad correlations between dam operations and aspects of trout populations across many dams and we are in the process of preparing a manuscript based on these results, which will be submitted for publication in FY14.

We propose to complement this broad assessment with in-depth analyses of tailwaters that contain a rich time-series of information. This new set of analyses will be focused on assessing the mechanisms behind salmonid growth as they relate to dam operations (e.g., prey availability, temperature, nutrients) using a subset of high-quality fishery data from the Colorado River Basin that spans 20+ years. For example, does discharge volume and/or hydropeaking directly influence trout size, or does discharge indirectly influence trout size through another variable (e.g., prey availability or nutrient inputs from the reservoir). Since all the data for this analysis are already collected, we expect to begin our work within FY14, with the expectation that it will spill over into FY15. We will prepare one manuscript for publication associated with the new analysis in FY15.

In addition to the mechanistic model developed in FY15, we propose to apply bioenergetics models developed for rainbow trout in Glen and Marble Canyon to other data-rich tailwaters in the Colorado River Basin (CRB) to further elucidate mechanisms responsible for differential performance on trout fisheries. By applying the same modelling format to different tailwaters, it should ease our ability to interpret differences between Glen Canyon and other tailwater systems. We have high-quality fishery, growth, foodbase, temperature, discharge, and reservoir data from Flaming Gorge Dam, which is the system that is most comparable to Glen Canyon Dam in the CRB. However, it differs from Glen Canyon because it has a selective withdrawal device that allows modification of the thermal regime (a phenomenon that may occur naturally below Glen Canyon resulting from climate change), it differs in invertebrate composition, and its trout population is composed of >50% brown trout. Brown trout are highly efficient predators (Yard and others, 2011), and their population expansion has been of concern in the Colorado River downriver of Glen Canyon Dam. Therefore, we propose to develop a bioenergetics model for the

Flaming Gorge tailwater that is similar to the model currently being developed for Glen Canyon, which will examine how prey size, water velocity, temperature, and rainbow and brown trout density (competition) influence the growth potential of rainbow trout. In addition, we may also construct a bioenergetics model for the tailwater below Navajo Dam. The Navajo tailwater lacks thermal modification and differs from Glen Canyon and Flaming Gorge in its flow regime (no hydropeaking), invertebrate assemblage, and brown trout density (~39%). Comparison of Glen Canyon to other tailwaters from a bioenergetics perspective will yield important insights that will be useful in the management of Glen Canyon Dam operations. We will prepare one manuscript in FY16 associated with these bioenergetics models.

Project Element 9.9. Effects of High Experimental Flows on Rainbow Trout Population Dynamics

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Dan Buscombe, Research Geologist, USGS, GCMRC
Thomas Gushue, Computer Specialist, USGS, GCMRC

The objective to this project element is to determine the effects of fall HFEs and other potential management actions, such as the Fall Steady Flow treatments of 2011-12, on rainbow trout populations in Glen Canyon. The purpose of the contingency plan as originally proposed (*GCMRC FY2013-14 Workplan, Project Element H.3*) was to determine the effect of a single fall HFE on age-0 trout densities. Although spring floods were known to have a large effect on early life stages of age-0 trout (Korman and Campana, 2009), there was considerable uncertainty about the effect that fall floods had on the survival of age-0 trout due to seasonal differences in growth (Melis and others, 2012). Typically, age-0 fish have a higher mortality rate than adults, yet rates begin to stabilize through late-summer into fall (Korman and others, 2011). The experiment was originally designed to estimate age-0 trout density and survival during pre- and post-flood periods, and then compare estimates between years with and without experimental floods. Currently we have successfully estimated changes in the apparent survival across two successive HFEs, flow events that had different magnitudes and durations, but due to hydrology we have been unable to acquire data during a year without an experimental flow.

The sampling design uses two mark-recapture trips that are conducted annually during early- and late-fall and samples the entire 25 km reach between Glen Canyon Dam and Lees Ferry. On average a total of ~5,000 fish are tagged with passive integrated transponders (PIT tags) per trip to determine site-specific capture probabilities for estimating age-0 fish abundance. A second trip is repeated in late-fall, to estimate across-trip survival and growth using recapture information from the previous trip. Although age-0 trout densities were estimated to be very high at the inception of the research study (fall 2011) successive marking efforts conducted in 2012 and 2013 have each required an additional 10-day sampling trip per year to tag sufficient numbers of trout (~10,000 age-0 trout quota) for the Natal Origin Project (*see Project Element 9.2*). For this reason we propose a continuation of funding for fall marking trips through FY2016, when at that time the Natal Origins research project will transition to monitoring led by AGFD. Funding for this project will support additional fieldwork and tagging efforts necessary for meeting the Natal Origin research objectives, as well as providing a means to further evaluate multiple fall-HFEs over a range of different age-0 fish densities. Also, efforts were started in fall 2013 to assess change in Glen Canyon channel-bed texture (Natal Origins Reach 1) in response to August 2013 fine-sediment inputs to that reach from Waterholes Canyon (the reach being imaged with side-scan sonar in October and December 2013 to bracket the November 2013 HFE, as well as in April 2014 to assess evolving shorelines and bed textures relative to ongoing trout monitoring and research.

Project Element 9.10. Examining the Effects of High Flow Experiments on the Physiological Condition of Age-0 and Adult Rainbow Trout in Glen Canyon

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Luke Avery, Fishery Biologist, USGS, GCMRC
Michael Yard, Fishery Biologist, USGS, GCMRC
Josh Korman, President, Ecometric Research, Inc.
Theodore Kennedy, Research Aquatic Ecologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

The objective of this research is to quantify the effect of lower and steadier fall flows (~5,000 ft3/s) followed by an HFE on the physiological condition and growth of age-0 and adult rainbow trout in Glen Canyon.

In fall 2012 and 2013, the Federation of Fly Fishers raised concerns regarding the potential effects of lower and steadier fall flows followed by an HFE on the foodbase for rainbow trout in Glen Canyon. Although previous research indicates that steadier flows can increase the growth rate of age-0 rainbow trout (Korman and Campana, 2009), and spring-timed HFEs can increase their survival and growth (Korman and others, 2011), it is unclear how lower and steadier fall flows (5,000-8,000 ft3/s) followed by a potentially energetically costly HFE may influence the growth and physiological condition of rainbow trout during a season where prey are typically limited. It is also unclear how quickly the trout population recovers following such an event, and whether the response for age-0 and adult fish differs. Therefore, this research will assess rainbow trout condition by using total lipid mass and lipid classes (e.g., storage fats, triacylglycerols) as sensitive biochemical indicators of physiological condition. In addition, otoliths of age-0 rainbow trout will be collected in post-flood fish to examine their daily growth rate in the weeks prior to and following an HFE to assess response and recovery time. These data will be compared to food base data collected prior to, during, and after the HFE. In addition, data will be collected in fall during a non-HFE year to compare rainbow trout condition and growth in a normal year to those influenced by an HFE.

Field sampling to collect fish will largely be incorporated into existing research and monitoring trips (Project Elements 6.7 [RTELSS], 9.2 [Natal Origins], and 9.9 [HFE/Fall Marking]), but additional electrofishing trips may be necessary. Total lipid will be extracted gravimetrically from whole-body age-0 fish and from adult tissue samples (Bligh and Dyer, 1959; Phillips and others, 1997), and total lipid will be separated into lipid classes using high-performance thin layer chromatography (Churchward and others, 2008; Zhou and others, 2012). Otoliths will be extracted from age-0 rainbow trout (Secor and others, 1991) collected during an HFE year and prepared for growth rate analysis using the distance between daily increments pre- and post-flood (Gilliers and others, 2004; Amara and others, 2009). In addition, age-0 otoliths will be checked for a “check” (a dark line indicating daily growth rings are placed very close together) to determine whether growth is interrupted in response to environmental conditions prior to and during the HFE. Growth rate measurements will be compared to those from fish captured during a non-HFE year to account for normal seasonal fluctuations in growth that occur regardless of the occurrence of a controlled flood.

Project 10. Mapping Flow Inundation of Shoreline Areas and Bed Textures in Glen and Marble Canyons

A. Investigators

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B. Project Summary

The overall objective of this research project is to evaluate physical characteristics within segments of the Colorado River channel in Glen and Marble Canyons relative the river's shorelines and bed textures. During the last two years, GCDAMP stakeholders have expressed interest in FY 2015-17 studies in Glen Canyon intended to evaluate dam releases below 8,000 ft^3/s that have occurred during water year 2014. In support of such proposed research, both Project 3 and this project element will provide aquatic ecology and foodbase projects with channel geometry and bed grain-size at Four-Mile Bar and other low-angle shoreline areas within Glen Canyon that are required to evaluate low-flow influences on the foodbase (*see projects 5.1 and 5.2*). Shallow, nearshore areas as well as deeper parts of the channel are both thought to be important to primary production and aquatic food base, and rainbow trout spawning and juvenile trout rearing. Better quantification and understanding about how varying dam releases inundate shorelines used by juvenile rainbow trout throughout Glen Canyon requires more detailed channel topography than currently exists in the Glen Canyon tailwater. Currently, developing hyposometric profiles (a simple, but nonlinear relationship showing area of shoreline covered by water at a range of river discharges) is likely possible for Glen Canyon from Lees Ferry upstream to about Six-Mile Bar, where shoreline and channel topography were previously obtained in 2004 and 2009. Upstream of Six-Mile Bar, full topography of the channel has not yet been collected, and only widely spaced cross sectional data exist, but are not closely co-located with nearshore juvenile trout nursery areas to be fully informative to Natal Origin of Rainbow Trout (NO) fishery or foodbase researchers. Depending upon which of the several hypotheses regarding trout growth are supported by research (*see project elements 9.3, 9.4, 9.6, and 9.8*), recruitment of juvenile trout tied to use of low-angle near-shore habitats in late spring and summer seasons (Korman and others, 2011) might be experimentally managed throughout the tailwater using flow treatments patterned over specific stage ranges and changing flow rates. Hence, design of future flow experiments to manage the trout population in Lees Ferry, might be informed using flow/habitat information resulting from combined analyses of fish sampling data and shoreline-habitat inundation mapping. This new project, in combination with Project 3, intends to provide the additional data about physical channel characteristics that will allow more detailed assessments and understanding about how dam releases influence life history strategies of invertebrates and rainbow trout in Glen and Marble Canyons.

C. Proposed Work

C.1. Project Elements

Specific objectives of this proposed integrated tailwater research include: 1) providing fish and aquatic foodbase researchers with data (stage discharge relationships, cross-sectional information on channel area, and channel-bed substrate distribution) to better inform the primary production model (Yard and Kennedy BWP 2013-14, and research proposed by Kennedy and others in 2015-17); 2) identifying stage and flow relationships within low-angle shorelines used by juvenile trout in Glen Canyon (Korman and others, 2011) to better understand the feasibility of experimental trout management dam releases to regulate early life history stages (age-0) of rainbow trout; 3) provide physical channel geometry data needed for addressing NO issues regarding spatial heterogeneity effects on capture probabilities within and among the four NO study reaches (*see project element 9.2*); 4) determining the abundance, distribution and grain-size characteristics of possible spawning gravel found in Glen and Marble Canyons; 5) determining the spatial and temporal variability in possible spawning gravel areas of the river bed in NO reaches over periods for which bed imagery is available; 6) evaluating the possible effects of changes in sand deposits (low elevation eddy and lower channel sandbars) resulting from high-flow dam operations relative to fish catch rates in NO reaches; and 7) integrating physical and biological data into a synthetic paper about dam operations, the foodbase and trout responses. One critical objective of this project is to quantify the low-angle nearshore areas that become available to fry after they emerge from redds over the lower range of allowable dam releases from 5,000 to 8,000 ft^3/s, as well as higher flows, including typical daily MLFF operations annually, and HFEs ranging up to about 45,000 ft^3/s. Observations in 2011 by NO researchers of juvenile trout using shallow inundated shorelines within Glen Canyon under high and steady dam operations, and the resulting survival of record numbers of fry that year (Korman and Yard, preliminary population estimate, 2012), warrant evaluation of the range of dam releases that create rearing areas for trout. A few examples of hypsometric profiles, constructed on the basis of single 2-dimensional cross sections and flow/stage rating curves, already exist at several sites in Glen Canyon (Melis and others, preliminary data, USGS, January 2014 Annual Reporting Meeting). However, owing to the placement of the available cross sections from these areas, such as Four-Mile Bar where most redds are observed, the flow and inundation relationships characterized at these limited downstream cross sections are not likely representative of shallower nearshore areas along other portions of the Lees Ferry tailwater.

Below Glen Canyon, areas of Marble and Eastern Grand Canyon have been previously mapped at high resolution (Grams, Buscombe and others, preliminary data, USGS, 2014) using swath multi-beam bathymetry, but discharge and inundation characteristics of nearshore habitats used by juvenile trout have not been previously evaluated downstream of Lees Ferry. The location of the USGS gage at 61-Mile (gage 09383100), also provides an opportunity to document shoreline habitat inundation upstream of the Little Colorado River confluence, while existing channel topography data downstream of the Little Colorado River to about river mile 64, and an existing 2-dimensional flow model (B. Logan, preliminary model, USGS, 2012) now make evaluation of nearshore habitat in these reaches also possible in 2015-17.

Gravel spawning areas for rainbow trout in Glen and Marble Canyons have been previously described (Korman and others 2005; Kondolf and others, 1989). Trout spawning continues to be monitored in Glen Canyon annually (see element H.2), but much less is known about whether gravel grain size used by spawners in Glen Canyon has changed at sites such as Four Mile Bar over time, or whether new gravel spawning areas have developed in Marble Canyon since initial studies were done in the 1980s. Previously collected topographic and digital imagery of Marble Canyon have been obtained through a variety of methods associated with earlier mapping and monitoring projects and are available in FY 2015 for use in development of quantitative methods for estimating areas below Glen Canyon with suitable rainbow trout spawning substrates. This research is needed now, as preliminary 2013-14 data from the NO project suggests increased local production of rainbow trout in Lower Marble Canyon has occurred since the project started in fall 2011 (Korman and others, Ecometric Research and USGS, preliminary data). Sand budgeting and channel topography data collected from 2009 to 2012 from lower Marble Canyon (Grams and others, USGS, 2014, preliminary data) also suggest that dam operations since 2009 have created a sand deficit in this segment such that channel conditions below river mile 30 may have become more suitable for rainbow trout spawning and rearing.

Topping and others (2003) report that dam operations under MLFF during the 1990s resulted in flows exceeding those required to accumulate sand on the river bed between Lees Ferry and Phantom Ranch – by about a factor of two compared to the pre-regulated era. This fact also further supports the idea that MLFF dam operations since 1996 have likely winnowed bed conditions in parts of Lower Marble Canyon where rainbow trout from natal origin areas upstream might find suitable spawning substrates after moving downstream from Glen Canyon. Because typical MLFF dam operations were shown not to accumulate multi-year tributary sand inputs on the bed of Marble Canyon after 1996, a protocol was implemented in 2012 to experimentally determine if more frequent HFEs could rebuild and maintain sandbars following Paria River tributary floods. More frequent HFEs that deposit sand deposits from the deeper channel to shorelines within eddies may, however, also create conditions of bed winnowing in deeper parts of the channel in lower Marble Canyon; scoured areas which could increase availability of suitable spawning habitat for rainbow trout.

Using existing channel topography data, we will determine hypsometric flow inundation curves along shorelines sampled for rainbow trout and native fish by Project H in 2015-17. Products will include maps showing shorelines inundated by flows of 5,000, 8,000, 15,000, 25,000, 31,500 and 45,000 ft^3/s, and this channel geometry information will also support data needs of food base researchers (*see Projects L.2.2 and L.2.4*). In an attempt to better use channel-bed imagery data to support fish and foodbase research, we will develop completely or partially supervised bed texture classification algorithms using existing sidescan data and validate these methods using concurrent video observations and multibeam backscatter. We will also pursue computational advances necessary for correcting a boat-mounted sidescan transducer for attitude instabilities (heave, roll, pitch and yaw) and evaluate the effects on sidescan image quality, using data collected from Marble Canyon in 2013 and Eastern Grand Canyon in 2014. The computational means will be developed by which sidescan data can be corrected for bed slope effects, when bed bathymetry is available, and we will also systematically characterize bed sediments in sidescan data collected in September 2000 (Anima and others 2007). Finally, within detection limits of data and methods used for image analysis and mapping, we will identify trends in sand versus gravel channel bed-area textures from existing channel-bed topographic or imagery data collected within NO study reaches (and to the extent possible, adjacent segments upstream) between 2009 (or earlier if data exist) and 2015. This is the main interpretive element intended to link areas of the channel associated with 1) drifting and emergent insects (*Projects 5.1 and 5.2*) and 2) rainbow trout spawning and early life history (*Project 9*) to changing physical conditions of the Colorado River channel (*Project 3*), in the context of other quality-of-water environmental attributes (turbidity and water temperature) within Glen and Marble Canyons (*Project 2*) already being evaluated within the 2015-17 budget and workplan.

Project 11. Riparian Vegetation Monitoring and Analysis of Riparian Vegetation, Landform Change and Aquatic-Terrestrial linkages to Faunal Communities

A. Investigators

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Joel B. Sankey, Research Geologist, USGS, Grand Canyon Monitoring and Research Center
Daniel Sarr, Ecologist, USGS, Grand Canyon Monitoring and Research Center Charles B. Yackulic, Research Statistician, USGS, Grand Canyon Monitoring and Research Center
Theodore A. Kennedy, Research Aquatic Ecologist, USGS, Grand Canyon Monitoring and Research Center
Emily Palmquist, Ecologist, USGS, Grand Canyon Monitoring and Research Center

B. Project Summary

Riparian vegetation affects physical processes and biological interactions along the channel downstream of Glen Canyon Dam. The presence and expansion of riparian vegetation promotes bank stability, diminishes the magnitude of scour and fill during floods, and has a role in wildlife habitat and recreational values. This project utilizes annual field measurements and digital imagery for integrated monitoring of changes in vegetation within a hydro-geomorphic context. Research elements of this project utilize the monitoring data to explore the utility of plant response-guilds to probabilistically evaluate and assess wildlife habitat, and integrate the response guilds with a 22-year topographic survey record for retrospective analyses of sandbar change for 20 selected sandbars. This project builds upon accomplishments associated with the FY13/14 workplan, provides information that support stakeholder needs as identified by guiding documents developed by the Adaptive Management Program, and furthers our understanding of the role of riparian vegetation in ecosystem processes within a regulated river setting.

The objectives and project elements of this monitoring and research project are:

1. Measurement and analysis of plant cover and species presence to assess change as related to the geomorphic setting, stage elevation, and dam operations (Element 11.1 annual ground-based monitoring)
2. Mapping changes in woody vegetation at the landscape scale through image processing, classification and analysis (Element 11.2 landscape scale change detection of vegetation, including analysis of tamarisk defoliation by the tamarisk leaf beetle (*Diorabda elongata*)
3. Utilizing vegetation response-guilds for integrated research of sandbars and riparian vegetation (Element 11.3 Utilizing response-guilds and sandbar monitoring data for a retrospective analysis of sediment and vegetation feedbacks to understand sandbar evolution in Grand Canyon)
4. Use multiple sampling approaches and historic data sets to quantify the strength of aquatic-terrestrial linkages and the relative importance of vegetation change and aquatic production in driving the population dynamics of a subset of the terrestrial fauna

(Element 11.4 Linking dam operations to changes in terrestrial fauna – the potential significance of vegetation change and insect emergence)

5. Each of these objectives and the associated project elements inform stakeholders about the status of vegetation and support analysis of vegetation's role in the ecological, physical, sociocultural responses to dam operations.

C. Proposed Work

C.1. Project Elements

Project Element 11.1. Ground-based Vegetation Monitoring

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Emily Palmquist, Ecologist, USGS/GCMRC
Todd Chaudhry, Restoration Ecologist, Grand Canyon National Park, NPS
Dustin W. Perkins, Program Manager, Northern Colorado Plateau Inventory and Monitoring Program, NPS

Work Category: Required monitoring

Objectives

- To annually collect vegetation data (presence, cover) within a geomorphic and hydrologic framework downstream of Glen Canyon Dam.
- To use the traits of the plants found to identify plant response-guilds
- Data and results are collected and described in a manner that can be utilized by multiple stakeholders for monitoring approaches used by Tribal stakeholders, and for use in basin-wide riparian vegetation monitoring programs overseen by the National Park Service's Northern Colorado Plateau Network Inventory and Monitoring Program

Hypotheses/Questions

General hypotheses or questions

1. Tracking response guild frequency as determined through annual data collection is an effective way to monitor directional responses of the riparian community and the river channel to dam operations.
2. Response guild identification is an effective method of grouping of plants that multiple stakeholders can use to describe long-term changes in vegetation.
3. Expansion of representative guilds to the Colorado River Basin provides an approach to assess riparian vegetation response in unregulated and regulated rivers.

Methods

The study area consists of four river segments whose limits are defined by the influence of tributaries and by floristic communities (Glen Canyon, Marble Canyon, eastern Grand Canyon, western Grand Canyon; fig. 2). The confluences of the Paria and Little Colorado Rivers and Kanab Creek with the Colorado River are points that divide the four segments. These river segment designations also overlap with suspended sediment sampling stations and work focused on sediment budgets that bracket Marble Canyon and eastern Grand Canyon (see Project 2). Further, assessing response guilds within short river reaches can help stakeholders identify areas that may be more or less responsive to dam operations. Species lists obtained from plot sampling (described below) within these river segments can inform park management of areas where undesirable species occur in greater abundance and allow a more focused approach to controlling these species.

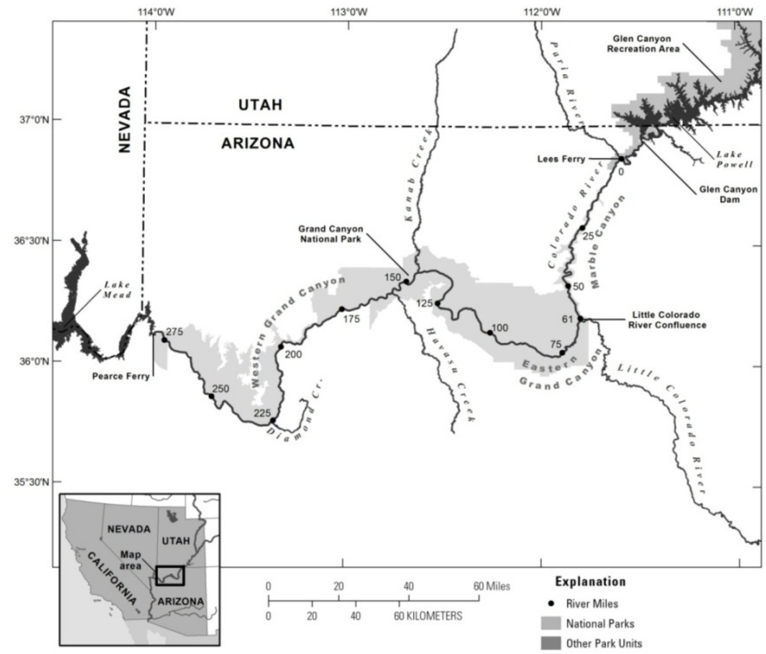

Figure 2. Four landscape-scale reaches used for stratification (Glen Canyon, Marble Canyon, Eastern Grand Canyon, and Western Grand Canyon). The confluences of the Paria, and the Little Colorado Rivers, and Kanab Creek with the Colorado River separates the four reaches.

Ground-based sampling

Sampling is intended to be complementary with the Big River Protocol of the NPS Northern Colorado Plateau Network (Scott and others, 2011), which includes fixed sites and randomly sampled plots that are matched to geomorphic features (e.g., reattachment bar, separation bar, debris fan, channel margins). Sampling downstream from Glen Canyon Dam will follow a similar approach. Fixed sites will be coincident with sandbar monitoring sites (Hazel and others, 2010, see Project 3.1) and channel mapping segments (USGS, 2011), see Project 3.2. Random sites will be stratified and equal numbers of geomorphic features will be sampled within river segments. Response guild identification was initiated in 2012 in collaboration with D. Merritt using species lists and data collected from 2001-2005 (Kearsley and others, 2006) and Stevens and others (1995) from 1991-1993 and data collected in 2012. These guilds continue to being refined as monitoring data are added to the database.

Fixed site sampling

Sampling sites are coincident with sandbar and channel monitoring sites. Among the potential sites that can be sampled (50 sandbars and the river channel data from RM 30 to 87), sandbar sites that are most and least responsive to high-flow events (HFEs), as measured by changes in sand volume and area (Hazel and others, 2010; Schmidt and Grams, 2011). Because the 50 sites in Project 3 are surveyed and sandbar area and volume calculated, the relationship between vegetation plot locations, associated plant response guild (derived from plot samples) and stage elevation can be determined. Monitoring vegetation response guilds at sandbars that are measured for responses to HFEs and other dam operations can help address physical resource questions about causes of variability in sandbars response. Specifically, this co-located data collection effort can support the monitoring and research question 4 presented in Project 3 with respect to the role of vegetation and the type of vegetation present on a sandbar affecting sandbar response to HFEs.

Plots at fixed sites will consist of 1-m^2 quadrats that are stratified across geomorphic features within a debris-fan eddy complex (upper pool, debris fan, separation bar, reattachment bar). The number of quadrats sampled will be proportional to the area of each feature. For example, a reattachment bar may be half the size of a separation bar and would have 50% fewer plots sampled. Plots will be randomly placed within each geomorphic feature. Their location will be identified prior to going in the field on aerial photos of the site. The 22-cm resolution of the 2009 imagery provides an ability to approximate plot location. Randomized plot points generated prior to sampling trips will ensure unbiased sampling. Because the sandbar sites are topographically surveyed annually (Project 3), the topographic information can be used to determine river flow necessary to inundate plots. This reduces the time necessary to locate permanent plots and obviates the need to monument plots. The vegetation monitoring determines annual changes in response guilds to dam operations and informs managers about how these changes may affect geomorphic features. Data collected will include cover and species presence. Plot data will also provide species richness and diversity and distinguish between native and nonnative species (table 1).

Random site sampling

The objective of random site sampling is to augment the fixed site sampling. Plot sampling here is limited to the area affected by annual dam operations including HFEs. Sampling includes an equal number of sandbars, debris fans, and channel margins within each river segment. One-meter square quadrats are used and data collected will be on species presence and total vegetative cover. Selection of random sites occurs prior to the sampling trip to ensure the sites are logistically feasible. Quadrats will be located along transects that are perpendicular to the channel. Because the locations will be determined prior to launch of the trip, the height above river level to the 45,000 ft^3/s stage can be determined using established stage elevation relationships and flow routing models (Griffin and Wiele, 1996; Hazel and others, 2006). Having the known river discharge for a particular day and time of day can assist in determining distance upslope to reach the 45,000 ft^3/s stage. Successive plots along the transect line will be sampled. These results will be compared with the fixed sampling site results for an assessment of the river segment and total river corridor.

Analysis

Data are collected annually at the end of the growing season (September/October) to capture vegetation response to changes in annual flows that may include short-duration flood pulses. These sampling approaches will also capture non-flow related interactions (e.g., tamarisk leaf beetle) that affect changes in community composition. The data result in descriptive metrics outlined in Table 2 and are also used to determine response guilds. For many of the common species, the physiological traits that are related to hydrology (disturbance tolerance, inundation capacity, drought tolerance), reproductive mode (seed only, vegetative), growth form, life span and salinity tolerance are determined for species encountered, primarily from the PLANTS database (www.usda.gov). These traits are used in a classification procedure to statistically determine the plant-response guilds (fig. 1). The number of species within each guild and the number of guilds will change as more trait information is quantified and added.

Table 2. Data collected for all plots and interpretation

Objective	**Data**			**Inference Goal**	
	Raw	Summarized		Trend	Statistic(s) for status
Estimate temporal change in riparian and wetland plant communities	Herbaceous spp			Y*	$\bar{x}$ % cover/sp; p plots/sp
		spp richness		Y	$\bar{x}$ richness
		Total herbaceous		Y	$\bar{x}$ % cover
		PI		Y	$\bar{x}$ index value
	Woody spp			Y*	$\bar{x}$ % cover/sp; p plots/sp; $\bar{x}$ no./m^2
		Total woody		Y	$\bar{x}$ % cover; p plots; $\bar{x}$ no./m^2
	Exotic spp			Y*	$\bar{x}$ % cover/sp; p plots/sp
		spp richness		Y	$\bar{x}$ richness
		Total exotics		Y	$\bar{x}$ % cover; p plots
	Litter			Y	$\bar{x}$ % cover
	Bare ground			Y	$\bar{x}$ % cover

Timeline

Work and reporting schedule.

	FY 15	**FY 16**	**FY 17**
Field work	September, October	August, October	August, October
Meeting w/NPS, Tribes	February	February	February
Draft Report	May	May	May
Final Annual Report	December	December	December

Products

- Annual species list
- Annual monitoring report describing changes in cover and species occurrence along the river corridor. Description of changes in indicator species and changes in frequency of vegetation response-guilds.
- Peer-review journal articles on response-guilds as a monitoring tool for rivers in the southwestern United States.

Project Element 11.2. Periodic landscape scale vegetation mapping and analysis using Remotely Sensed Data

Joel Sankey, Research Geologist, GCMRC/USGS
Laura Cagney, Research Specialist, GCMRC/NAU
Barbara Ralston, Supervisory Biologist, GCMRC/USGS

Work Category: Required monitoring

Objectives

1. The ***primary objective*** of this project element is to produce an accurate and current remote sensing image-based classification of vegetation.
2. The ***secondary objective*** of this project element is to quantify stability and changes in vegetation composition from the comparable "system-wide" classification of vegetation that was last completed for imagery collected in 2002 to 2013.

Addressing the fundamental questions and hypotheses associated with this objective are contingent on the first objective that will result in a 2013 vegetation classification that is as good as or better than the classification based on 2002 imagery. This assessment of stability and change in vegetation composition will span a decade of river-management characterized by reduced powerplant operations and 3 controlled floods, as well as the appearance of the tamarisk leaf-beetle (Diorhabda carinulata) in portions of the CRe. Importantly the 2013 classification can also be added to the long term assessment of riparian vegetation encroachment for select reaches (Waring, 1995) of total vegetation from 1965 to 2013 that was successfully completed using data through 2009 in the FY-14/15 workplan. (This work will be completed by Laura Cagney in collaboration with Joel Sankey).

3. A ***tertiary objective*** will be to attempt to cross-walk the composition of vegetation in the image-based classes from 2013 and 2002 with composition of response guilds identified in other project elements (Element 10.1.) associated with riparian vegetation.
4. A ***sub-element*** of the project element will specifically attempt to detect and map the extent of tamarisk leaf beetle effects for remotely sensed vegetation canopies from overflight imagery from 2009 to 2013.

Hypotheses/Questions

1. *The fundamental question is what is the composition of riparian vegetation, and how does it vary spatially throughout the CRe, based on 2013 imagery? The ability to address the fundamental question of this objective is contingent upon successful, accurate classification of vegetation based on the 2013 imagery.*

The classification will be derived from the high resolution (20 cm pixel size) multispectral remote sensing imagery from the May, 2013 overflight for the entire river corridor of the CRe.

This will produce a new and most up-to-date assessment of the presence, absence, and composition of vegetation in the CRe. (This work will be completed by Laura Cagney).

2. *How has the vegetation composition in the CRe changed within the approximately 1-decade monitoring period from 2002 to 2013?*

We anticipate that changes from 2002 to 2013 will reflect a suite of environmental conditions identified by previous work at GCMRC; including very recent work completed during the FY 13/14 workplan. Based on previous work we hypothesize that (i) temporal stability and changes in vegetation classes (composition) will vary by river stage-elevation zone, and (ii) compositional changes by elevation zone will be indicative of effects of regional precip (e.g., drought) at higher elevations, and river hydrology (e.g., flow duration) at lower elevations. Moreover, we know from work completed during the FY13/14 workplan that the long-term, post-dam trajectory of increased vegetation expansion at increasingly lower elevation zones occurred during the 2002 to 2009 time period at stage-elevations well below the maximum of recent controlled floods. Therefore, we will ask whether increases and decreases in vegetation at these lower stage-elevations (i.e., inundated during operations that include controlled floods between 2002 and 2013) vary by vegetation class composition? In particular, we will focus on identifying the range of (and most common) classes of vegetation that bare ground (e.g., sand) transitioned to from 2002 to 2013. Finally, we know that the tamarisk leaf beetle appeared in portions of the CRe during the time period of our vegetation composition change analysis and therefore we will ask whether the spatial variability in changes in the abundance of the class containing tamarisk exists and if so, whether it correlates to understanding of where the tamarisk leaf-beetle existed pre-2013?

3. *The question asked in this objective is whether the composition of vegetation in the image-based classes from 2013 and 2002 can be cross-walked with the composition of response guilds identified in other riparian vegetation project elements in a manner that produces a useful and accurate, landscape-scale assessment of spatial variability in (at least some of the) response guilds?*

To the extent possible, we will then ask how the spatial variability in the detectable response guild(s) have and have not changed during the approximately 1-decade time period. To the extent possible, the decadal change in relative abundance of detectable response guilds can be quantified. (Completed by Joel Sankey in collaboration with Barbara Ralston and Daniel Sarr).

4. *The question asked in this objective is whether beetle-impacted stands of tamarisk can be detected and successfully mapped by independent and combined analysis of 2009 and 2013 imagery in select reaches where the leaf beetle are known to have appeared since approximately 2009. The second question is whether variability and changes in remotely sensed characteristics of the tamarisk canopies (e.g., greenness, cover, leaf area) can be detected and attributed quantitatively to the presence of the leaf beetle.*

This sub-element will be performed for specific reaches where the beetle appeared since 2009, including (1) Kanab Creek in Grand Canyon, (2) within Glen Canyon, as well as (3) a control reach not yet impacted by the leaf beetle. (Completed by NAU M.S. student Ashton Bedford with Joel Sankey and Barbara Ralston serving as thesis committee members).

Methods – Primary Objective

Preparation of 2013 imagery mosaic and shoreline masks

Before vegetation analysis can begin, the 2013 imagery must be mosaicked from flight lines received from the contractor, and broken down into standardized GCMRC Quarter-Quarter-Quad boundaries. This process includes the required reflectance value or digital number histogram matching. Another critical step before vegetation analysis can begin is to produce a shoreline, this also creates the ability to remove known open water pixels from further analysis. Depending on the sediment load of the 2013 imagery this process can be executed using a Green/Red band ratio extraction or a principal components approach. The Green/Red band ratio extraction compares the values of the green band to the red band, these two reflectance values are uniquely different when trying to isolate open terrestrial water and will result in a dataset that represents the May 2013 shoreline at a steady 8,000 ft^3/s water discharge.

Total vegetation map

We will produce a total vegetation database and a vegetation class database with at least 6 vegetation classes for the entire river corridor up to the top of the Old High-Water Zone (at the 250,000 ft^3/s flow stage) using image processing of remotely sensed data. Normalized Difference Vegetation Index (NDVI) is a commonly used method to segregate total vegetation in multispectral data, a more robust and accurate method is the Spectral Angle Mapper (SAM), which was used in mapping with the 2009 imagery and is proposed for use with the 2013 dataset. The SAM technique provides the vector angle between the wavelength-band values of an image pixel user determined to be vegetation. The smaller the vector angle, the more similar the image pixel is to user-designated vegetation. Both sunlit and shadowed vegetation spectra will be used in the SAM analysis in order to map all vegetation, even within shadows. If image band data are consistent throughout the corridor, then the range of SAM values for vegetation should also be consistent, or at least vary systematically throughout the canyon, allowing the vegetation to be mapped quickly. The range of SAM values for vegetation will be determined interactively using the image result from the SAM output and the corresponding color-infrared image. To determine corridor consistence and variability, SAM ranges will be determined every 8 km of the corridor; if the derived SAM ranges are consistent or vary systematically, then the observed SAM range relation will be used to map the total vegetation throughout the canyon. The results for each of the 126 image tiles that cover the river corridor will be examined for accuracy and the SAM range adjusted when necessary. If the initial SAM ranges at 8 km increments are random, then the SAM range for every image tile will be independently determined and applied interactively to provide an accurate total vegetation database.

Vegetation classification

Once total vegetation is segregated in the 2013 image data set (anticipated by or before summer 2016), a most-likely vegetation species will be assigned to each image pixel based on reflectance angle. Even though final mapping will probably occur at the response guild or association level (categories of classification within the National Vegetation Classification Standard (FGDC, 2008)), the spectral band quality of the 2013 imagery are very different in terms of dynamic range, consistency, and accuracy and, therefore, the level of the final vegetation map for this database will not be known until the species classification is completed. Species classification will be accomplished using the following information, in order of preference: (1) ground observations that were collected in August and September 2013; (2) ground-truth site observations that occurred during other image acquisitions, where it is determined by visual examination of the periodic images that certain vegetation is the same in the image data being analyzed; and (3) our previously collected ground-reflectance database for the common vegetation species within the canyon. Image classification will proceed in 8-km increments progressing downstream in the river corridor from Glen Canyon Dam, because vegetation composition and the spectral properties of species gradually change downstream.

Image classification will be based mostly on the image-band signatures and canopy texture of representative vegetation species (Davis and others, 2002). Species classification using the 2013 image data will use a supervised classifier, such as Maximum Likelihood, SAM, or Neural Net. We will experiment with various classifiers to determine the classifier that is most robust and produces the highest map accuracies for most vegetation species. We will use the same canopy texture measures that were employed for the 2002 vegetation mapping, although the areal dimensions of the spatial tools may change due to the higher spatial resolutions of the 2013 image data compared to that of the 2002 image data, the most recent vegetation map from GCMRC.

Undoubtedly, there will be ambiguities in the final species classifications, because the spectral and textural characteristics of some species overlap. We will try to reduce the ambiguity using knowledge of dominant species within particular ecotones related to river stages, although care will be exercised within the riparian zone not to exclude xeric species. When the species classification process reaches the point of diminishing returns, a statistical accuracy assessment will be performed on the 2013 results, and a determination will be made as to the aggregation levels for their final vegetation databases. We will also incorporate approaches used in Grand Canyon National Park's vegetation-mapping project to develop compatible layers and classes of vegetation.

Methods – Objective 2

Total vegetation from 2013 will be used to extend the long-term change analysis conducted for the FY13/14 BWP using the GIS and statistical methods previously developed and described. Change and stability in vegetation classes from 2002 to 2013 will be summarized by stage-elevation zone, and by units of debris fan, channel margin, and eddy areas as represented in the canyon-wide geomorphic base map (see Project A.1.2). Relationships of temporal variability in vegetation composition by elevation zone and by geomorphic unit will be examined relative to variability in flow duration by elevation zone and the expected response to regional drought from 2002 to 2013. Changes to the abundance and spatial distribution of the class containing tamarisk will be examined longitudinally throughout the corridor and tested for significant differences between reaches where leaf beetles have been and have not been documented.

Methods – Objective 3

The composition of the mapped vegetation classes and response guilds will be compared to determine whether any of the response guilds or aggregates of functionally similar guilds can be accurately represented by individual or aggregate vegetation classes. If some classes or aggregates are successfully identified as potential proxies for response guilds, spatial and temporal variability from 2002 to 2013 will be examined using the change detection and summary methods described for the secondary objective.

Methods – Objective 4

Supervised classification methods will be used to map foliated tamarisk within the study reaches using 2009 and 2013 imagery. The classifications will potentially incorporate the 4 multispectral bands from the imagery in addition to NDVI, EVI and leaf area index (LAI). The classification will be developed from training pixels in the study reaches that represent foliated tamarisk stands. Change analysis of the area mapped as foliated tamarisk in 2009 and 2013 will be conducted. Change analysis will also consider relative changes in the indices (NDVI, EVI, LAI) for locations where foliated tamarisk was mapped as present in one image date and absent in the other, as well as present or absent in both dates. Ground-based point observations of known beetle populations (pers comm, Levi Jameson) will be used identify the relationship between changes in presence and remotely sensed canopy characteristics of tamarisk stands and beetle populations.

Timeline

Work and reporting schedule.

	FY 15	**FY 16**	**FY 17**
Primary Objective	X	X	
Secondary Objective		X	X
Tertiary Objective			X
Sub-element	X		

Project Element 11.3 Influence of sediment and vegetation feedbacks on the evolution of sandbars in Grand Canyon since 1991 (FY15-17)

Daniel Sarr, Research Ecologist, USGS/GCMRC
Paul Grams, Research Hydrologist, USGS, GCMRC
Barbara Ralston, Supervisory Biologist, USGS/GCMRC
Pat Shafroth, Research Ecologist, USGS, Fort Collins
Emily Palmquist, Ecologist, USGS/GCMRC
Joseph E. Hazel, Research Associate, NAU
David M. Merritt, Research Ecologist, U.S. Forest Service

Work Category: High priority research

Objectives

To understand the interplay between hydrology, vegetation and sediment dynamics among 20 sandbars for a 23-year period (1991 to 2013) by using long-term sandbar monitoring data, instantaneous discharge record, sediment transport information, intermittent vegetation sampling data, riparian plant response guilds, and aerial and oblique repeat photography.

Hypotheses/Questions

1. *How does establishment of vegetation nearer the channel (below stage at power plant capacity (877* m^3/s*) influence sediment sandbar maintenance (net deposition and scour) associated with experimental high flows?*
2. *Does expansion of woody riparian vegetation below stage elevations of power plant capacity (877* m^3/s*) and associated sediment response decrease shoreline complexity and negatively affect native fish rearing habitat (side-arms) and riparian habitat (compositional and structural complexity)?*
3. *In a regulated, debris fan-eddy river system does expanded floodplain development on reattachment bars result in smaller eddy circulation zones and hence a smaller river with reduced temporary storage capacity, or do river currents fundamentally change and affect sediment storage and transport capacity?*

Methods

The retrospective analysis uses multiple data sources (Table 3). Topographic surfaces from 1991 to 2013 of selected sandbars will be used to compute the elevation changes across years for transects across sandbars and following high flow events. Using plant-response guilds (based on traits associated with water acquisition and fluvial disturbance, but also grouped based on traits that influence hydraulics) and exceedance probabilities associated with the instantaneous discharge record for each year, we will make occurrence probability maps for plant guilds across the sandbar surfaces for each year. The daily repeat photography will be used to verify guild representation. Repeat aerial imagery will be used to estimate canopy cover. The intermittent vegetation sampling data will also be used to determine guild occurrence relative to predicted guilds and support estimated cover values for guilds. This approach will give a time-series of vegetation succession based on annual hydrology that is also coupled with observed sandbar morphologic change. We propose to do this analysis for 20 sandbars distributed throughout the canyon.

The linkage between vegetation change and geomorphology will be strengthened with numerical flow modeling. The purpose of the modeling that is underway in the FY13-14 work plan is to examine processes by which vegetation-stabilized bar areas affect flow and deposition. The modeling proposed for this study will be used to establish relations between the vegetation response-guilds and flow parameters such as velocity and shear stress for high flows. Models will be developed using roughness values for vegetation obtained in the literature and applied to the guilds. For example, roughness for tamarisk or willow that co-occur in a guild (Table 1) may be applied for all plants associated in the guild. The age of guilds will be determined from the vegetation succession time-series process described above. Age of guilds provides a proxy for the stem diameters of vegetation within a guild. This information and canopy cover estimates that can be used to estimate stem stiffness that influence hydraulics and sediment transport in the water column (Griffith and others, 2014; Kean and Smith, 2004). Available velocity profiles and suspended sediment data will also be used in this modeling effort (McDonald and Nelson, 1996; Wright and Kaplinski, 2011). Subsequent year change in sandbar topography can be used to verify expected versus observed sediment response. This approach would be done for a subset of the 20 sandbars described in the retrospective analysis for vegetation change. The subset will be distributed upstream and downstream of the Little Colorado River to account for tributary effects on sediment inputs related to sandbar response.

Table 3. Summary of topographic, sediment transport, imagery and vegetation sample data available for sandbars

Data type	Dates collected	Reference
Instantaneous (15 minute interval) discharge at Lees Ferry	1921 to present	Topping and others 2003
Sediment transport data	1996, 2000, 2004, 2008, 2012, 2013	Webb and others, 1999; Schmidt and others, 2007; Grams and others, 2013
High-precision Topographic surveys (±0.05m ground point precision)	Annually since 1991	Hazel and others, 2008, Kaplinski and others, 2014;
Stage-discharge relations	1990-2005	Hazel and others, 2007
Oblique Imagery	Intermittently since 1991	USGS, unpublished data
Aerial imagery (orthorectified)	2002, 2009, 2013	Davis, 2013, 2012
Vegetation sample plots	1995, 2001-2005, 2012-2013	Kearsley and Ayers, 1995; Kearsley and others 2006; USGS unpublished data, 2012-13.

Timeline:
Work and reporting schedule.

	FY 15	**FY 16**	**FY 17**
1st quarter	Data Consolidation, Parameter Identification, Initial methodology outlined	Application of methodology to successive bars	Manuscript development
2nd quarter	Preliminary analysis for 5 sandbars	Status Report	Draft Manuscript
3rd quarter	Status Report	Results	Submission of manuscript
4th quarter	Methods Report and initial results	Draft Report	December

Deliverables:
Progress report FY15, AGU presentation
Draft Report FY16
Manuscripts FY17

Project Element 11.4 Linking dam operations to changes in terrestrial fauna – the potential significance of vegetation change and insect emergence

Charles B. Yackulic, Research Statistician, USGS/GCMRC
John Spence, Resource Manager, Glen Canyon National Recreation Area, NPS
Jeff Muehlbauer, Aquatic Ecologist, USGS/GCMRC
Charles Drost, Research Wildlife Biologist
Barbara Ralston, Supervisory Ecologist, USGS/GCMRC

Theodore Kennedy, Research Aquatic Ecologist, USGS/GCMRC
Daniel A. Sarr, Research Ecologist, USGS/GCMRC
Emily Palmquist, Ecologist, USGS/GCMRC

Work Category: High priority research

Objectives

1. *Determine the degree to which populations of terrestrial animals respond to spatial and temporal variation in aquatic insect emergence along the Colorado River, with an initial focus on the Glen and upper Marble Canyon reaches.*
2. *Identify whether long-term chances in vegetation have influenced populations of terrestrial consumers, particularly birds and terrestrial insects in the Glen Canyon reach.*
3. *To the extent possible, determine the links between terrestrial fauna and vegetation-flow response guilds.*

Hypotheses/Question

1. Can we detect long and/or short-term trends in avian populations by combining historical and newly collected data in an occupancy framework? Are short-term trends for insectivores linked to changes in annual aquatic production?
2. To what degree does swallow and bat activity track spatial and temporal patterns in insect emergence from the Colorado River? Can their activity serve as a continuous noninvasive index of insect emergence?
3. How have terrestrial arthropod communities responded to relatively recent changes in dam operations, including increased frequency of HFEs (which may remove litter); how have communities changed in response to increasing impacts of tamarisk beetle?
4. How are aquatic-terrestrial subsidies structured spatially and do spiders distribute themselves to take advantage of these subsidies? What proportion of spider consumption is based on terrestrial versus aquatic sources?

Methods

This project element utilizes information gained from the vegetation response-guild work and insect emergence monitoring conducted in FY13-14. It will also include some analysis of historic data, particularly breeding bird data collected in the 1990s in the Glen Canyon reach and studies of terrestrial arthropod communities ~5 years ago. This project will also involve field work to collect new data. Broad tasks for this project follow.

1. Investigate changes in the abundance and distribution of breeding bird populations in Glen Canyon using methods and fixed locations previously surveyed by John Spence (National Park Service) in the 1990s, and reanalyze both the historic and new data using occupancy methods.
2. Develop methods for quantifying the abundance and distribution of swallow and bat species, and test whether feeding concentrations are closely linked to patterns of emergence, as we hypothesize. Possible approaches include cost-effective remote automated cameras positioned to capture hourly pictures of swallows and fixed acoustic recorders for quantifying bat activity and species composition. Additionally, we will also develop standardized techniques for quantification of swallow abundance and bat activity that can be used throughout Grand Canyon by citizen scientists.

3. Determine how terrestrial arthropods, especially spiders, are distributed and how communities have changed since surveys led by Ralston in 2009 (Ralston and others, in review), particularly in response to increased frequency of high flow events and changes in vegetation. This work will be supplemented by collection of isotope data for a subset of spider samples to quantify the actual percentage of food obtained from aquatic sources.

Project 12. Dam-Related Effects on the Distribution and Abundance of Selected Culturally-Important Plants in the Colorado River Ecosystem

A. Investigators

Helen Fairley, USGS, Grand Canyon Monitoring and Research Center
Peter Bungart, Hualapai Tribe
Tony Joe, Navajo Tribe
Mike Yeatts, Hopi Tribe
Charley Bulletts, Kaibab Band of Paiute Indians
Kurt Dongoski, Pueblo of Zuni

B. Project Summary

This proposal aims to document the historical distribution and relative abundance of a subset of plants that are known to have been culturally important to multiple Native American tribes, including specifically the tribes currently involved in the AMP. This study would serve as one basis for assessing dam effects to the river corridor's cultural landscape. This study will be accomplished through comparing historical photographs of locations exhibiting specific targeted species with more recent photographs of those same locations, and it will also incorporate direct observations of many of those locations, to compare past and current vegetation conditions. This project will involve systematically analyzing historical photos of the river corridor in an office setting as well as in the field, to qualitatively and quantitatively assess changes to species of particular cultural importance to tribes during the past 20 years, as well as over longer time intervals.

In addition to evaluating changes in the distribution and abundance of specific culturally-valued plants, Tribes may elect to participate in this project by using some of the historical photographs that are associated with places of particular cultural importance to each tribe to solicit feedback from tribal members as to whether they view the documented changes in a positive or negative light, and why. These observations can be incorporated into ongoing tribal monitoring projects, some of which are already exploring the utility of historical photographs for this purpose (e.g., Hualapai Tribe, 2013).

This project will serve the interests of the tribes involved in the GCDAMP, as well as the interests of all AMP stakeholders, in several important respects. Specifically, this project will: 1) utilize traditional ecological knowledge to inform DOI managers and GCDAMP stakeholders about dam-related changes affecting culturally-valued vegetation species and larger river corridor/ cultural landscape; 2) integrate Native American values and traditional ecological knowledge in a collaborative GCMRC-sponsored science effort; 3) utilize traditional ecological knowledge to further enhance connections between tribal youth and elders. In addition, this project will address a long-standing interest of multiple AMP stakeholders who would like to see a variety of approaches, including more holistic and qualitative methods, used for assessing how Glen Canyon Dam is affecting the riparian landscape and diverse cultural values of the Colorado River corridor. Furthermore, it is aligned with the new Department of Interior directive to use a landscape approach for assessing and mitigating effects of energy-related projects on federal lands (DOI 2013, Secretarial Order No.330).

C. Proposed Work

This project will involve several components, some of which will employ semi-quantitative western scientific methods and others that will utilize qualitative assessments based on tribal perspectives. By semi-quantitative, we are referring to a proposed system of ranking changes observed from the historical images, as more precise quantitative methods may not be possible given the variable quality of the imagery. Methods specific to each elements are described below.

C.1. Project Elements

Project Element 12.1.

At the outset of the project, GCMRC will host a one-day workshop involving tribal members, GCMRC program staff, and riparian ecologists from USGS and NPS. The purpose of this workshop will be to review and compare lists of plant species developed by tribes during previous ethnobotanical research projects (e.g., Lomaomvaya and others, 2001) and identify a subset of plant species that are of common interest to all the tribes that have good potential to be readily recognized in historical photographs. The list of selected species, which is anticipated to include 6-8 individual species, will become the focus of subsequent analysis efforts. The final list of species will be determined through consultation with the tribes, but are likely to include Goodding Willow (*Salix gooddingii*), Net-leaf Hackberry (*Celtis reticulate*), Indian Rice Grass (*Oryzopsis hymenoides*) and Dropseed (*Sporobolus sp.)*

After the list of target species has been identified, GCMRC staff will undertake a systematic analysis of historical photos from the Stanton expedition (1890) and recent matches made by Dr. Robert Webb and colleagues in 1990-1991 and 2010-2011, plus other historical data sets such as photographs taken during the 1923 Birdseye Expedition and photographs taken by H Butchart, R. Euler, and D. Schwartz in the 1960s. This analysis will be carried in conjunction with similar analyses being undertaken for other purposes as part of Project 4 and will also involve direct collaboration with staff of the Hulaapai Tribe who have initiated similar types of analysis for a pilot TEK project in FY13-15.

Using analytical methods previously developed by Webb (1996) for comparing the 1890 and 1990 Stanton photos, GCMRC staff will systematically analyze and qualitatively assess changes to specific plants of traditional cultural importance to tribes that have been collaboratively identified for this project. The analysis will also qualitatively characterize the context in which the plants occur, noting any apparent physical changes to local context associated with observed plant changes (e.g., differences in characteristics of fluvial deposits, biological soil crust cover, aeolian sand cover, vegetation growth, etc.) Specific protocols will be established for recording these observations to ensure consistency, comparability and reliability of resulting data but will likely involve a systematic ranking of observed changes (e.g., high, moderate, low, none). The resulting data may be used to supplement and complement more quantitative data being collected by ongoing GCMRC projects (Projects 3, 4, and 11) by providing additional time-depth perspectives about local landscape changes at specific locations throughout the river corridor.

While conducting these analyses, photographs taken at or near locations that are currently monitored by the Tribes will be identified for potential incorporation into future tribal monitoring trips.

GCMRC staff will assess the reliability of observed changes by field checking a sample of the documented changes based on analysis of photographs with actual conditions in the field. This work will be accomplished in conjunction with river trips that are planned for other projects, such Projects 3, 4 and 11, tribal monitoring trips, or Grand Canyon Youth trips.

Project Element 12.2.

After an initial review of the available historical imagery by GCMRC, Tribal staff may elect to select a subset of the identified photographs at locations of particular importance to each tribe. On their annual monitoring river trips, tribal members will relocate each photo and compare the historical photo view to current conditions. Following an established protocol (to be developed in cooperation with GCMRC), tribal members will analyze changes in plant species by comparing the historic photos (1890, 1923, 1990, 2010) with current conditions. (Tribes may also want to include a photo duplication component – TBD.)

Tribal staff will use the information obtained from the field photo comparisons to elicit tribal member input about their perceptions of the observed changes, i.e., whether a change is perceived as positive, negative, or neutral. The underlying basis for each perspective/ assessment will be elicited through semi-structured interviews and will be documented, either through recording the interview with a tape recorder or video camera or by completing a structured interview form. This information is expected to complement and enhance other information being collected during annual tribal monitoring trips. The results of the semi-structured interviews will be incorporated into a final report for this project, and may also be incorporated into annual tribal monitoring reports, as appropriate.

Project 13. Socio-economic Monitoring and Research

A. Investigators

Lucas Bair, Economist, USGS, Grand Canyon Monitoring and Research Center
Charles Yackulic, Research Statistician, USGS, Grand Canyon Monitoring and Research Center
John Duffield, Research Professor, Department of Mathematical Sciences, University of Montana
Chris Near, Researcher, Department of Mathematical Sciences, University of Montana
David Patterson, Professor, Department of Mathematical Sciences, University of Montana
Michael Springborn, Assistant Professor, University of California at Davis
Craig Bond, Economist, Pardee RAND Graduate School

B. Project Summary

Over the past three decades, socioeconomic monitoring and research in the Glen Canyon Environmental Studies and Glen Canyon Dam Adaptive Management Program (GCDAMP) have been limited (Hamilton and others, 2010). Previous research has indicated that the economic value of recreation and other downstream resources are impacted by Glen Canyon Dam (GCD) operations; however, because these studies were conducted 20 to 30 years ago, the findings may no longer be relevant as dam operations and resource conditions have changed since that time (Bishop and others, 1987; Welsh and others, 1995; U.S. Department of Interior, 1996; USGS, 2005).

This project is designed to identify recreation and tribal preferences for, and values of, downstream resources and evaluate how preference and value are influenced by variation in GCD operations. In addition, the research will integrate economic information with data from long-term and ongoing physical and biological monitoring and research studies at the Grand Canyon Monitoring and Research Center (GCMRC) to construct a decision support system that will improve the ability of the GCDAMP to evaluate and prioritize management actions, monitoring and research (Hamilton and others, 2010).

This project involves three related socioeconomic monitoring and research studies. These studies include: (a) evaluation of the impact of GCD operations on regional economic expenditures and economic values associated with angling in the Glen Canyon National Recreation Area (GCNRA) below GCD, and whitewater floating in Grand Canyon National Park (GCNP) specific to floaters using the Lees Ferry launch site (project element **13.1**); (b) assessment of the impact of GCD operations on tribal preference for and value of downstream resources (project element **13.2**); and (c) development of decision methods, using economic metrics, to evaluate management actions and prioritize monitoring and research on resources downstream of GCD (project element **13.3**).

This project will be coordinated with related economic research efforts implemented by the National Park Service (NPS) and U.S. Bureau of Reclamation (Reclamation) in conjunction with the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS). The NPS is conducting research to provide current economic values of ecosystem resources downstream of GCD. In addition, Argonne National Laboratory, contracted through Reclamation, has made significant advancements in the power system analysis modeling for the LTEMP EIS that provide information on the economic value of hydropower production at

GCD under different management alternatives. These coordinated efforts to determine individual preferences for and economic values of downstream resources, and the development of decision methods to improve decision making abilities of GCDAMP are necessary to evaluate and prioritize management, monitoring, and research decisions.

C. Proposed Work

C.1. Project Elements

Project Element 13.1. Economic Values of Recreational Resources along the Colorado River – Grand Canyon Whitewater Floater and Lees Ferry Angler Values ($108,241)

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Chris Near, Researcher, Department of Mathematical Sciences, University of Montana
David Patterson, Professor, Department of Mathematical Sciences, University of Montana

The objective of this project element is to determine preferences, regional expenditures, and economic values of anglers in GCNRA[1] and whitewater floaters in GCNP, as affected by operation of GCD, to provide the GCDAMP and federal decision-makers with current recreation resources information for decision making processes. This project element has been initiated with FY 2013-14 funds from Project K, Economist and Support ($241,305). The funding request for FY 2015-16 is for continued involvement of the GCMRC economist, Lucas Bair.

To accomplish the project objective, a series of economic surveys will be conducted to obtain current information on recreationists' preferences, expenditures, and economic values associated with angler and whitewater floater trips. Specifically, surveys of anglers in GCNRA and whitewater floaters in GCNP will include questions addressing:

- Regional expenditures associated with trip activities such as the cost of transportation, lodging, guide services, and various other local purchases.
- Trip attributes of importance such as crowding, fish catch characteristics, overall trip enjoyment, and other trip qualities.
- Direct recreational use values (i.e., net economic benefits) to the recreationist, as measured by willingness to pay over and above trip costs.
- Variation in direct recreational use values related to a range of flow levels presented in the surveys.

As was the case with the original Bishop and others (1987) study, the proposed project will use a mail survey contact method with a follow-up protocol for non-responders. The respondents will be sent a mail survey packet, followed by a postcard reminder, and, later, by a second survey packet for non-responders. Non-respondents to the second survey packet will be contacted to complete non-response questions.

A random sample from the most recent year whitewater floaters will be obtained with the assistance of GCNP and outfitters. Grand Canyon National Park maintains a comprehensive

[1] For purposes of this project element, anglers in GCNRA include walk-in anglers from Lees Ferry to Badger Creek Rapid.

mailing list of all members of private whitewater floater parties. Additionally, commercial outfitters maintain mailing lists of the commercial clients. The survey will include: 1) private party floaters, 2) commercial motor powered floaters, and 3) commercial oar powered floaters. The target sample size will be 2,850 whitewater floaters divided equally between private and commercial trip participants. The commercial sample will be further divided equally between oar and motor-powered trips.

Anglers in the Lees Ferry area will be contacted during high use periods, spring (April-May) and fall (October-November), to participate in the surveys. No *a priori* attempt will be made to stratify the sampling based on guided or non-guided status. However, preferences, expenditures, and economic values of guided and non-guided anglers will be compared within the data analysis. Anglers contacted at Lees Ferry will be asked questions regarding demographics and attributes of their trip. In addition, anglers will be asked to provide contact information. The target sample size is 750 anglers.

Statistical models appropriate for the experimental design and elicitation format of the surveys will be developed to evaluate the relationship between preferences, economic value and trip attributes (e.g., flow levels). The models will provide information on the relative preferences and economic value for trip attributes and the marginal rates of substitution between trip attributes. This information is necessary for the GCDAMP to make informed decisions about the economic tradeoffs that occur, with regard to recreation, when evaluating future management actions (see FY2015-17 Workplan, Project Element **13.3.***)*.

Project Element 13.2. Tribal Perspectives for and Values of Resources Downstream of Glen Canyon Dam ($374,824)

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The objective of this project element is to identify tribal preferences and values associated with management of resources downstream of GCD in order to inform decision making processes in the GDDAMP. Emphasis will be placed on resources of tribal significance that are directly or indirectly affected by dam operations, experiments, and ongoing management. The assessment of tribal preferences and values will be achieved through focus group meetings with individual tribes, where choice experiment methods will be conducted to explicitly evaluate resource attributes and related impacts from operation of GCD. The assessment of tribal preferences and values will be initiated in FY 2016, subsequent to, and coordinated with, ongoing GCMRC economics studies.

The individual project elements will consist of four major tasks:

1. Cooperate with GCDAMP Tribal representatives and Tribal members to review previous studies and tribal programs relating to the Colorado River Tribes' preferences for and values of resources downstream of GCD and obtain necessary permits to conduct research on tribal land.

2. Conduct initial meetings with individual tribes to obtain permission and gauge interest in participation, identify focus group participants, and develop and pretest focus group survey content to ensure culturally appropriate methodology.
3. Conduct focus group meetings with individual Colorado River Tribes to explore preferences for and values of downstream resources. The meetings will use choice experiment methods (Breffle and Rowe, 2002; Harpman, 2008), which are commonly applied in marketing and resource economics studies, to identify these preferences and values.
4. Analyze survey results and prepare manuscript for publication.

For the choice experiment methods, resource attributes of tribal importance (e.g., hydropower, humpback chub) 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 possible scenarios to choose from, where respondents may be asked to evaluate all possible scenarios or just a subset of randomly chosen scenarios if the number of choices are unwieldy. Based on input during tribal consultation, future attribute levels will be either ranked, rated, or evaluated in a choice-based format (two alternative future scenarios compared and one is selected). It is important to note that comparisons between resource attributes can contain explicit cost information (e.g., forgone hydropower revenue) when comparing future resource attributes, or may just compare resource attributes alone. Statistical models appropriate for the experimental design and elicitation format will be developed to evaluate the relationship between preferences, or values, and resource attributes. The models will provide information on the relative preferences and values for resource attributes and the rates of substitution between resource attribute tradeoffs.[2] Information gained through this research is necessary for evaluation of management decisions and development of applied decision methods that accommodate tribal preferences for and values of downstream resources (*see FY2015-17 Workplan, Project Element* **13.3**).

Project Element 13.3. Applied Decision Methods for the Glen Canyon Adaptive Management Program ($392,198)

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Michael Springborn, Assistant Professor, University of California at Davis
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The objective of this project element is to, through the application of economic analysis, develop a decision support system, comprised of a series of analytical models, that informs the prioritization of monitoring, research, and long-term management alternatives in the GCDAMP. The models will incorporate economic parameters and provide prompt assessment capabilities in science and management program planning.

To accomplish this, existing decision theory methodology will be evaluated. Specific attention will be paid to methods that improve decision making processes when evaluating resource tradeoffs related to monitoring, research, and management decisions. Evaluation efforts will focus on decision frameworks and analytical tools that best apply to the GCDAMP when

[2] Model results will not quantify the economic value of the resource attribute. However, if price based attributes (e.g. hydropower costs) are assessed in the surveys, economic values can be ascertained.

considering the need for collaboration, complex biophysical/socioeconomic interactions, and constraints on GCDAMP resources.

There are multiple analytical approaches used in decision frameworks that address resource management under uncertainty. These include maximizing expected utility, applying the precautionary principle and other robust decision making processes such as dynamic stochastic programming, optimal control, or simulation methods (Lempert and Collins, 2007). The various approaches differ in the types of scientific information utilized and the way in which decision process outcomes are framed and communicated (Lempert and Collins, 2007).

There are also various types of decision support system frameworks that are important to consider when interdisciplinary teams of scientists and stakeholder groups that hold divergent views, or core values, are involved in the decision process. It is as important to address the decision process, or context, as it is to develop the scientific foundation, or content, of the analytical methods (Norton, 2005; Clifford and Sagoff, 2009).

This project element will develop and implement a decision support system specific to the GCDAMP in a series of model development tasks. Analytical model development of downstream resources will be prioritized for resources that:

1. Contain significant economic value and/or that garner a significant portion of the GCMRC annual budget;
2. Are impacted by operational decisions at GCD; and
3. Have sufficient predictive modeling frameworks developed to assess future resource states.

For example, the initial focus of this project element will be the development of a bioeconomic model to identify the economically preferred control strategy for established nonnative fish, in relation to humpback chub survival. This is a question explicitly identified in the NNFC (Reclamation, 2011). This task follows the model prioritization structure, (1) ecosystem values (including humpback chub) exhibit significant economic value (Welsh and other, 1995); (2) dam operation impacts non-native fish populations (see FY2015-17 Workplan, Project Element **9.7.1** and **9.7.2**), and (3) recent advancements in predictive models of rainbow trout and humpback chub survival have led to opportunities to evaluate humpback chub population management from an economic perspective (Yackulic and others, 2014). This task will evaluate economic outcomes, as part of the Yackulic and others (2014) model, to minimize the cost of rainbow trout removal over time, under different future scenarios. While the exact methodological approach will be determined through model development, the likely approaches include optimization (stochastic dynamic programming or optimal control) and/or simulation based approaches (Epanchin-Niell and Hasting, 2010). Incorporating future scenarios allows for modeling humpback chub recovery goals in various conditions while identifying strategies that are both cost-effective and robust to uncertain future conditions (e.g., climate). This analytical model, and accompanying documentation, will be completed in FY 2015.

This proposed bioeconomic model utilizes cost-effectiveness analysis. Like cost-benefit analysis, cost-effectiveness analysis is a standard economic practice. However, cost-effectiveness fundamentally asks a different question than cost-benefit analysis. Cost-benefit analysis assigns an overall net benefit (or net cost) to a future management action. Cost-effectiveness analysis in-turn identifies the least cost alternative, when faced with competing or complimentary management actions, to reach a defined objective. In this case, the objective is humpback cub recovery, as defined by the recovery goals (U.S. Fish and Wildlife Service, 2002). Implementing cost-effectiveness analysis is consistent with the ROD's goal, not to maximize benefits but to determine an operation at GCD that limits impact to hydropower while meeting recovery and long-term sustainability of downstream resources (Reclamation, 1996).

There are several other implications when using cost-effectiveness analysis that are important to recognize. For example, it must be determined that the defined goal is worth achieving. This is demonstrated by either verifying the economic benefit of the objective outweighs the costs associated with achieving the objective or the objective is mandated through a public process. In the case of the humpback chub recovery goals, both the economic value of recovery exceeds the cost of proposed recovery actions and the recovery goals are mandated through public process (Welsh and others, 1995; U.S. Fish and Wildlife Service, 2002). Conducting cost-effectiveness analysis also implies that the defined goal will be reached across all possible alternative future scenarios. Again, this is a reasonable assumption based on the recovery mandate (U.S. Fish and Wildlife Service, 2002). This implication is important because it essentially removes the onerous, or in some cases contentious, identification of economic value of downstream resources. The focus is shifted from establishing the benefit of the objective to identifying the most cost-effective way to meet the objective (Sagoff, 2009). This is an important distinction when stakeholders may fundamentally reject attempts to economically value aspect of ecosystem resources. Cost-effectiveness analysis isn't appropriate in every context. However, it lends itself to the GCDAMP's task of evaluating and prioritizing management actions, monitoring and research where incremental decisions must be made, under uncertainty, understanding that many overarching objectives are set through public processes.

While the initial task is focused on research to identify the most cost-effective management actions with respect to non-native fish removal policies, as identified in the NNFC (Reclamation, 2011), the modeling effort will be expanded to include other downstream resources and better facilitate decision making in the GCDAMP. Specifically, subsequent tasks in model development will include:

1. Identify the importance of parameter uncertainty on the sensitivity of cost-effective outcomes in the bioeconomic model. Evaluating parameter uncertainty will aid in the identification of the value and prioritization of monitoring and research (i.e., how scientific discovery and monitoring, and reducing model parameter uncertainty, decreases expected management costs) and demonstration of how modeling can prioritize future monitoring and research. This advancement in the analytical model, and accompanying documentation, will be completed in FY 2016-17.
2. Incorporate additional control variables and associated costs, such as trout management flows at GCD, to improve humpback chub survival, again identifying the most cost-effective management alternatives under different future scenarios. This advancement in the analytical model, and accompanying documentation, will be completed in FY 2016-17.

The decision support system will be developed over FY 2015-17 in cooperation with stakeholders, according to stakeholder's expressed needs and the advancement of scientific knowledge at GCMRC. For example, updating the economic value of whitewater floating in the GCNP will provide insight into modeling the tradeoffs between flow experiments and recreational experiences (*see FY2015-17 Workplan, Project Element 13.1*) and understanding of non-native fish removal technologies, and associated costs, (*see FY2015-17 Workplan, Project G*) will expand control actions for non-native fish. This deliberate process of building a decision support system through the development of individual analytical, predictive models will enable analysts to identify monitoring and scientific information needs and screen policy options as the GCDAMP advances its goals. This process is essential in enabling the GCDAMP to better organize and evaluate the scientific monitoring and research that is provided by GCMRC.