U.S. Geological Survey
Grand Canyon Monitoring and Research Center

Glen Canyon Dam Adaptive Management Triennial Budget & Work Plan
Fiscal Years 2021-2023
Preliminary Draft

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

1. Investigators

David J. Topping, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Ronald E. Griffiths, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
David J. Dean, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

The primary linkage between Glen Canyon Dam operations and the characteristics of the physical, biological, and cultural resources of the Colorado River ecosystem (CRe) downstream from Glen Canyon Dam is through the stage, discharge, water quality, and sediment transport of the Colorado River. This project makes and interprets the basic measurements of these parameters at locations throughout the CRe. The data collected by this project are used to implement the High-Flow Experiment (HFE) Protocol (i.e., trigger and design HFE hydrographs), to evaluate the reach-scale sand mass-balance response to the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), and to evaluate the downstream effects of releases conducted under the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) (U.S. Department of the Interior, 2016a, b).

The data collected by this project are also required by most of the other physical, ecological, and socio-cultural projects funded by the Glen Canyon Dam Adaptive Management Program (GCDAMP). In addition to supporting the LTEMP sediment goal, the basic data collected by this project supports the following nine LTEMP goals: aquatic food base, archaeological and cultural resources, humpback chub, hydropower and energy, invasive fish species, natural processes, rainbow trout fishery, recreational experience, and riparian vegetation. Most of the project funds support basic data collection at USGS gaging stations, with the remainder funding interpretation of basic data. Roughly 64% of the proposed budget covers basic data collection, with the remaining 36% supporting salaries for serving the data and for interpretive work (i.e., publications). The funds requested under this proposal cover ~75% of the costs required to collect data at the network of USGS gaging stations used by this project. An additional $203,000 for this network is provided to the USGS Arizona Water Science Center from funds appropriated by Congress for the USGS, the Bureau of Land Management, and the Arizona Department of

2Environmental Quality (AZDEQ), and from funds provided by the Navajo Nation and Peabody Energy. This project is designed to provide measurements of stage (i.e., water elevation), discharge (i.e., streamflow), water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minute) to resolve changes in these parameters and to allow accurate determination of suspended-sediment loads for use in sediment budgeting (Grams and others, 2019; Topping and others, in review). The proposed monitoring under this project will be very similar to that conducted over the last 18 years. Work conducted under the previous workplan indicated that sand storage in the channel and sandbars is not likely sustainable in the CRe unless tributary sand inputs remain well above average and dam releases remain slightly below average. The work proposed in this current workplan is therefore the work required to address this conclusion.

3. Proposed Work

Project Elements

Project Element A.1. Stream Gaging and Hydrologic Analyses

This element partially funds the collection, serving, and interpretation of continuous 15-minute measurements of stage and discharge on the main-stem Colorado River at USGS streamflow gaging stations located at river miles (RM) 0, 30, 61, 87, 166, and 225, and at gaging stations on the major tributaries and in a representative subset of the smaller, formerly ungaged tributaries. Of the work conducted under this project element, almost all of the funding covers work at the main-stem Colorado River gaging stations and the gaging stations on the major tributaries. One to two major publications will arise from work conducted in this project element during this work plan.

Project Element A.2. Continuous Water-quality Parameters

This element funds the collection, serving, and interpretation of continuous 15-minute measurements of water temperature, specific conductance (a measure of salinity), turbidity, and dissolved oxygen at the outlet of Glen Canyon Dam and at the above-mentioned six main-stem Colorado River gaging stations. In addition, this project element funds continuous measurements of water temperature at additional stations on the Colorado River and in the major tributaries. Data collected under this project element will be used in publications led by investigators in other GCDAMP-funded projects.

Project Element A.3. Sediment Transport and Budgeting

This element funds the collection, serving, and interpretation of continuous 15-minute measurements and also episodic measurements of suspended sediment and bed sediment at the above-mentioned gaging stations on the Colorado River and its tributaries. In addition, this project element funds interpretive work in regard to the sand supply from the Paria and Little Colorado Rivers, and interpretive work in regard to the effect of dam operations on the sediment

resources in the Colorado River between Glen Canyon Dam and Lake Mead. The continuous suspended-sediment measurements at the six main-stem Colorado River gaging stations, and the episodic suspended-sediment measurements in the tributaries are used in the construction of mass-balance sand budgets and used to trigger, design, and evaluate HFEs. One to two major publications will arise from work conducted in this project element during this work plan.

Project Element A.4. HFE Experimental Fund

This element funds the collection and processing of streamflow and sediment data before, during, and after HFEs.

4. References

Grams, P.E., Schmidt, J.C., Wright, S.A., Topping, D.J., Melis, T.S., and Rubin, D.M., 2015, Building sandbars in the Grand Canyon: EOS, Transactions of the American Geophysical Union, v. 96, no. 11, p. 12-16, https://doi.org/10.1029/2015EO030349.

Grams, P.E., Buscombe, D., Topping, D.J., Kaplinski, M.A., and Hazel, J.E., Jr., 2018, How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise: Earth Surface Processes and Landforms, v. 44, no. 1, p. 160-178, https://doi.org/10.1002/esp.4489.

Topping, D.J., Grams, P.E., Griffiths, R.E., Dean, D.J., Wright, S.A., and Unema, J.A., *in review*, Self-limitation of sand storage in a bedrock-canyon river arising from the interaction of flow and grain size: Journal of Geophysical Research–Earth Surface.

U.S. Department of the Interior, 2012, Environmental assessment—Development and implementation of a protocol for high-flow experimental releases from Glen Canyon Dam, Arizona, 2011 through 2020: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 176 p. plus appendices, https://www.usbr.gov/uc/envdocs/ea/gc/HFEProtocol/index.html.

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

U.S. Department of Interior, 2016b, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

5. Budget

Fiscal Year 2021								
Project A	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 14.00%**	**Total**
A.1 Stream gaging and hydrologic analyses	$174,900	$4,200	$16,000	$20,700	$0	$245,100	$30,200	**$491,100**
A.2 Continuous water-quality parameters	$93,200	$800	$11,000	$20,700	$0	$27,400	$17,600	**$170,700**
A.3 Sediment transport and budgeting	$323,200	$5,000	$55,000	$20,700	$0	$147,600	$56,500	**$608,100**
Total Project A	$591,300	$10,000	$82,000	$62,100	$0	$420,100	$104,300	**$1,269,900**
A.4 HFE experimental fund (only used if HFE occurs)	$24,700	$1,000	$8,000	$18,800	$0	$0	$7,400	**$58,800**

Fiscal Year 2022								
Project A	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 24.00%**	**Total**
A.1 Stream gaging and hydrologic analyses	$184,600	$4,200	$16,000	$21,300	$0	$238,800	$54,300	**$519,200**
A.2 Continuous water-quality parameters	$96,000	$800	$11,000	$21,300	$0	$28,500	$31,000	**$188,600**
A.3 Sediment transport and budgeting	$350,200	$5,000	$55,000	$21,300	$0	$151,200	$103,600	**$686,300**
Total Project A	$630,800	$10,000	$82,000	$63,900	$0	$418,500	$188,900	**$1,394,100**
A.4 HFE experimental fund (only used if HFE occurs)	$25,300	$1,000	$8,000	$19,400	$0	$0	$12,900	**$66,600**

Fiscal Year 2023								
Project A	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 28.00%**	**Total**
A.1 Stream gaging and hydrologic analyses	$203,500	$4,200	$16,000	$22,000	$0	$232,500	$68,800	**$546,900**
A.2 Continuous water-quality parameters	$98,900	$800	$11,000	$22,000	$0	$29,700	$37,200	**$199,500**
A.3 Sediment transport and budgeting	$360,800	$5,000	$55,000	$22,000	$0	$154,800	$124,000	**$721,500**
Total Project A	$663,200	$10,000	$82,000	$66,000	$0	$417,000	$230,000	**$1,467,900**
A.4 HFE experimental fund (only used if HFE occurs)	$25,900	$1,000	$8,000	$19,900	$0	$0	$15,300	**$70,100**

Project B: Sandbar and Sediment Storage Monitoring and Research

1. Investigators

Paul E. Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Daniel Buscombe, Assistant Research Professor, Northern Arizona University
Joseph E. Hazel, Jr., Research Associate, Northern Arizona University
Matt Kaplinski, Research Associate, Northern Arizona University
Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Robert Tusso, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary

The purposes of this project are to: a) track the effects of individual High-Flow Experiments (HFEs) on sandbars and campsites, b) monitor the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics. These objectives are accomplished by annual measurements at long-term sandbar monitoring sites (B.1), periodic measurements of changes in riverbed sand storage (B.2), maintenance of a geodetic control network (B.3), focused studies of riverbed dynamics in the Western Grand Canyon (B.4), and development of a new streamflow model for Marble Canyon (B.5). Field activities that would occur for monitoring condition-dependent experimental actions such as HFEs are also described (B.6 – B.9). Results from this project are used to evaluate progress towards meeting the Long-Term Experimental and Management Plan (LTEMP) goal, to "increase and retain fine sediment volume, area, and distribution … for ecological, cultural, and recreational purposes."

3. Proposed Work

Project Elements

Project Element B.1. Sandbar and Campsite Monitoring with Topographic Surveys and Remote Cameras

The purpose of this project element is to monitor the annual status and long-term trends of sandbars and campsites in Glen, Marble and Grand Canyons. The results are used to evaluate the effects of dam operations, including HFEs, on sandbars and related resources. We propose to

continue annual measurements at the existing set of 45 long-term monitoring sites with topographic surveys that will be used to compute sandbar area and volume and usable campsite area (subset of 37 sites). In addition, this project will include maintenance of remote cameras for daily monitoring at 42 sites and implementation of machine-learning methods developed in the previous work plan for analysis of images to measure changes in sandbar area. A predictive model for sandbar response to dam operations developed in the previous work plan will be applied to evaluate the effects of different dam operations scenarios on sandbars (see Project element J.1). The sandbar database and website for serving sandbar data and images will be maintained and improved. Data collection for this project will occur on one non-motorized river trip each year.

This project also includes support for the Grand Canyon River Guides Adopt-a-Beach (AAB) program, which provides an assessment of campsite condition from the perspective of river guides. In this three-year work plan, we propose to conduct a synthesis of observations made by the AAB program since its inception in 1996 and integrate those observations with the annual campsite and sandbar monitoring measurements. We will supplement this analysis with an update to the Grand Canyon National Park campsite inventory, which was last conducted systematically around the 1996 controlled flood experiment (Kearsley and others, 1999).

Project Element B.2. Bathymetric and Topographic Mapping for Monitoring Long-term Trends in Sediment Storage

The primary purpose of this project is to track trends in sandbar conditions and sand storage over the time scale of the HFE protocol and the LTEMP and thereby provide a robust measure of whether the supply of sand (the sum of recent tributary inputs and background storage) necessary for building sandbars is increasing, decreasing, or stable. This project monitors changes in sand storage over long river segments, providing robust and spatially explicit quantification of changes in the channel, eddies and sandbars. The results from this project will be used to evaluate the outcome of the flow regime adopted in the LTEMP with respect to sandbar building and sand conservation. The measurements of sand storage in the channel are critical, because that information will be needed to explain the observed trends in sandbar area and volume and whether HFEs should be conducted more frequently or less frequently than prescribed in the LTEMP. This information will also be needed to assess whether the implemented flow regime is able to achieve sediment-related goals.

For this three-year workplan, we propose to conduct baseline bathymetric and topographic mapping for the segment between River Mile (RM) 87 and 166. This is the only segment between Glen Canyon Dam and Diamond Creek that has not been previously mapped. We also propose to collect repeat measurements for the segments between Lees Ferry and RM 30. These data, together with data collected for other segments in previous work plans, will be used to provide a 10-year assessment of LTEMP sediment-related objectives in 2026.

Project Element B.3. Control Network and Survey Support

The purpose of this project element is to provide a framework to enable high-accuracy change detection and to ensure that geospatial data collected in support of this project and other projects are accurately referenced, precisely defined, and can be reliably compared with past and future datasets. In FY 2021, this project element will provide substantial support to the remote sensing overflight (see Project L). Some expansion of the existing control network will be required for project element B.4 (see below).

Project Element B.4. Bank Erosion, Bed Sedimentation, and Channel Change in the Colorado River Arm of the Lake Mead Delta in Grand Canyon

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

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

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

This study will include repeat measurements of a short (~1 to 3 km) study reach (to be selected) downstream from Quartermaster Canyon. These data will be supplemented with numerical modeling to evaluate the relation between streamflow, sediment transport, and riverbed dynamics. Field work for this project will occur during a year with a fall HFE. We have, therefore, included the data collection costs associated with this project element in the experimental budget.

Project Element B.5. Streamflow Modeling

The purpose of this project element is to develop a new streamflow model for the Colorado River between Lees Ferry (RM 0) and Phantom Ranch (RM 87) in support of this project and other projects. Existing models provide good predictions for discharge and water-surface elevation, but because they are based largely on estimated "synthetic" channel geometry, they cannot be used to predict water depths, streamflow velocity, or bed shear stress. Predictions of these quantities are necessary for spatially explicit predictions of sediment, nutrient or veliger transport and quantification of physical habitat for fish, riparian and in-stream vegetation and invertebrates (including mussels). We propose to develop and calibrate a two-dimensional, hydraulic model for the whole of Marble Canyon, where extensive channel mapping data are available. The model will be used to provide the necessary boundary conditions required to run and validate morphodynamic sandbar models which are required to better understand the feedbacks between vegetation encroachment and sandbar dynamics, and to provide flow depth and velocity relations for habitat characterization.

Project Elements B.6-B.9. Sandbar and Riverbed Response to Experimental Actions (to be funded only when experiments occur)

The LTEMP Environmental Impact Statement (EIS) and Record of Decision (ROD) include two experimental activities designed to improve sandbar and sediment resources (extended duration HFEs and proactive HFEs) and one experimental activity that may cause increased sandbar erosion (trout management flows). The purpose of this project element is to collect and analyze field data that will be used to evaluate the effects of any of those flow experiments on sediment resources if and when those experiments occur.

- B.6. Extended-duration HFEs: Additional measurement of the sandbar monitoring sites before and after the extended HFE and daily surveys during the extended duration HFE at two locations. The daily surveys will allow for comparison between observed sandbar deposition rates and main-channel suspended sand concentrations. The proposed budget does not include a pre-HFE survey because it assumes that this occurs with regular monitoring.
- B.7/B.8. Proactive HFE: Surveys of sandbar topography immediately following the proactive HFE and again following the period of summer high-volume dam operations. The proposed budget does not include a survey following summer operations as it is assumed that occurs with regular monitoring. Project B.7 assumes that post-HFE surveys are conducted during normal operations (does not require bathymetry). Project B.8 assumes that post-HFE surveys are conducted during equalization operations (requires bathymetry).

- B.9. Western Grand Canyon: Collect four repeat surveys of a 1- to 3-km study reach in Western Grand Canyon before a fall HFE, during the HFE, ~2 weeks following HFE, and ~2 months following HFE.
- Trout management flows: Data collection will depend on the expected number of fluctuation cycles. If the trout management flow consists of only a few flow fluctuation cycles, the increased amount of erosion compared to normal fluctuations would likely be small and difficult to measure. Under this scenario, observations from existing remote cameras will be used to determine if sandbar erosion rates are affected by these flows. If the trout management flow consists of many fluctuation cycles, the expected additional erosion would require additional sandbar surveys to quantify sandbar change. Because of uncertainties in how these flows might be implemented, a budget has not been estimated.

4. Budget

Fiscal Year 2021								
Project B	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
B.1 Sandbar Monitoring	$155,896	$2,000	$2,000	$27,344	$205,408	$0	$32,376	$425,023
B.2 Sediment Storage Monitoring and Research	$170,742	$2,000	$34,200	$111,040	$197,408	$0	$50,440	$565,830
B.3 Control Network and Survey Support	$94,192	$0	$15,000	$0	$0	$0	$15,287	$124,479
B.4 Western Grand Canyon Sedimentation	$74,694	$0	$0	$0	$0	$0	$10,457	$85,151
B.5 Streamflow Modeling	$68,682	$1,900	$0	$0	$0	$0	$9,881	$80,463
Total Project B	$564,206	$5,900	$51,200	$138,384	$402,816	$0	$118,441	$1,280,946

Fiscal Year 2022								
Project B	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
B.1 Sandbar Monitoring	$183,968	$2,000	$11,000	$28,590	$196,224	$0	$60,021	$481,804
B.2 Sediment Storage Monitoring and Research	$183,968	$2,000	$4,000	$0	$188,224	$0	$51,239	$429,431
B.3 Control Network and Survey Support	$59,624	$0	$15,000	$0	$0	$0	$17,910	$92,534
B.4 Western Grand Canyon Sedimentation	$76,935	$0	$0	$0	$0	$0	$18,464	$95,399
B.5 Streamflow Modeling	$76,638	$1,900	$0	$0	$0	$0	$18,849	$97,387
Total Project B	$581,132	$5,900	$30,000	$28,590	$384,449	$0	$166,483	$1,196,554

Fiscal Year 2023								
Project B	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
B.1 Sandbar Monitoring	$189,487	$2,000	$11,000	$29,838	$205,408	$0	$71,213	$508,946
B.2 Sediment Storage Monitoring and Research	$189,487	$2,000	$8,000	$82,891	$197,408	$0	$84,988	$564,773
B.3 Control Network and Survey Support	$61,413	$0	$15,000	$0	$0	$0	$21,396	$97,809
B.4 Western Grand Canyon Sedimentation	$79,243	$0	$0	$0	$0	$0	$22,188	$101,431
B.5 Streamflow Modeling	$74,406	$1,900	$0	$0	$0	$0	$21,366	$97,672
Total Project B	$594,035	$5,900	$34,000	$112,729	$402,816	$0	$221,150	$1,370,631

LTEMP Experimental Projects	Funded only when experiments occur -- Based on Fiscal Year 2022 costs							
Project Description	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
B.6 Extended duration HFE (daily surveys during HFE + sandbar surveys w/o bathymetry)	$14,429	$1,200	$1,000	$81,470	$70,749	$0	$25,666	$194,514
B.7 Proactive HFE (sandbar surveys w/o bathymetry)	$14,429	$1,200	$1,000	$37,133	$44,253	$0	$14,230	$112,245
B.8 Proactive HFE (sandbar surveys with bathymetry)	$18,147	$1,200	$1,000	$62,609	$62,586	$0	$21,787	$167,329
B.9 Western Grand Canyon (4 surveys around fall HFE)	$8,270	$4,800	$3,000	$26,182	$94,016	$0	$12,961	$149,229

5. References

Kearsley, L.H., Quartaroli, R., and Kearsley, M.J.C., 1999, Changes in the number and size of campsites as determined by inventories and measurement, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 147-159.

Project C: Riparian Vegetation Monitoring and Research

1. Investigators

Emily C. Palmquist, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Brad Butterfield, Assistant Research Professor, Northern Arizona University, Center for Ecosystem Science and Society (ECOSS)

2. Project Summary and Purpose

Riparian vegetation affects physical processes and biological interactions along the channel downstream of Glen Canyon Dam in ways that are integrally linked to flow regime. Reduced peak flows and increased base flows have promoted riparian vegetation expansion close to the river but favor some species over others. Daily fluctuating flows have been shown to decrease germination, establishment, and survival of riparian plants and is likely impacting the species composition in the Colorado River Ecosystem (CRe). Flow patterns designed to enhance other important resources have a collateral impact on riparian vegetation. Riparian plant species differ in their societal, biological, and physical values (e.g., tall shade trees vs. thorny herbs), such that changes to species composition result in impacts to wildlife habitat, sediment scour and deposition, visitor experience, and many other natural processes.

Collectively, the four elements of this project assess riparian vegetation status in the CRe (Element 1), test mechanisms by which flow regime impacts species of interest (Element 2), synthesize data to anticipate changes to vegetation (Element 3), and assist non-flow management actions directed by the Long-Term Experimental and Management Plan (LTEMP) (Elements 2, 3, 4). Specifically, Element 1 collects and summarizes data that identify if the LTEMP riparian vegetation and natural processes goals are being met by annual measurement of plant species cover and composition. Element 2 addresses the LTEMP riparian vegetation and natural processes goals by determining why different types of flow scenarios favor some plant species over others. Element 3 synthesizes other data to address the LTEMP archeaological and cultural resources, natural processes, recreational experience, sediment, tribal resources, and riparian vegetation goals by modeling links among resources and by informing the LTEMP experimental vegetation treatment. Finally, Element 4 encompasses the LTEMP resource goals benefited by the LTEMP experimental vegetation treatment (archeaological and cultural resources, natural processes, recreational experience, sediment, tribal resources, and riparian vegetation*)* by providing data and analyses that are aimed to improve the efficacy of those management actions.

3. Proposed Work

Project Elements

Project Element C.1. Ground-based Riparian Vegetation Monitoring

Monitoring the status and trends of native and non-native plant species provides the information about diversity, abundance, health, productivity, sustainability, and ecological context required to determine if riparian vegetation and natural process goals are being met. Annual measurement of plant species cover and composition will be characterized for: (1) multiple geomorphic features representative of the CRe and (2) long-term monitoring sandbars and campsites. These data form the basis of vegetation status and trends reporting, and the backbone for modeling efforts. Stratified-random sampling of multiple geomorphic features provides a thorough assessment of vegetation composition, cover, richness, and native to nonnative species dominance on an annual basis throughout the CRe. Long-term monitoring sandbars and campsites provide a more focused assessment of the impacts of vegetation on recreational resources, and an opportunity for integration of vegetation and sediment dynamics.

Project Element C.2. Mechanistic Experiments with Plant Species of Interest

Manipulative experiments provide mechanistic insights into plant responses to flow regime that can inform predictive models of vegetation dynamics. The complex effects of daily and seasonal fluctuations in river flow, coupled with the dual roles of water as both a resource (depth to water table) and stressor (inundation duration) are difficult to tease apart from annual observational data alone. Manipulative experiments under controlled conditions outside of the CRe are a cost-effective way to identify effects of distinct components of dam operations on plant performance. Mechanistic experiments will focus on three species of interest with very different biological and resource characteristics: Goodding's willow (*Salix gooddingii*), a large native tree species frequently used in plantings for recreational (shade) and cultural purposes, but with low establishment success; Arrowweed (*Pluchea sericea*), a common native shrub that is increasing in cover on high value recreational beaches, negatively impacting campsite availability and aeolian sand transport; and Seepwillow (*Baccharis* spp.); native shrubs that have significantly expanded close to the river over the last 5-6 years that are emblematic of species that have increased in the area impacted by daily dam operations.

Project Element C.3. Predictive Modeling of Vegetation Responses to Dam Operations

Predicting vegetation responses to flow regime requires understanding how riparian vegetation responds to many different flow regimes across broad scales. Lags in vegetation responses to hydrological events and the lack of interannual flow variability in the CRe create the need to use

data derived from regional collaborations and manipulative experiments that expand the range of biophysical parameters used to construct vegetation models. This project element will integrate ground-based vegetation monitoring (Element 1), manipulative experiments (Element 2), and existing regional data on riparian vegetation composition and hydrographs using advanced statistical modeling. Once models are developed, specific components of the flow regime (for example, magnitude of daily fluctuations, magnitude and timing of environmental flows including High-Flow Experiments (HFEs), seasonal variation in base flows) will be varied through simulations in order to predict the sensitivity of multiple aspects of vegetation (for example, diversity, cover, non-native species, species of concern) to distinct aspects of the flow regime.

Project Element C.4. Vegetation Management Decision Support

LTEMP non-flow experimental vegetation treatment includes revegetation efforts with native species, as well as vegetation removal to support recreational and sociocultural resources. Success of these efforts depends upon the hydrological settings in which they occur, due to strong linkages between hydrology and vegetation performance. The detailed, species-specific niche models developed during the FY 2018-20 Triennial Work Plan for all of the common plant species in the CRe, along with the mechanistic experiments (Element 2) and predictive models (Element 3) proposed here, will be used to provide site-specific recommendations based on hydrological and climatic parameters. These predictions will be compared to monitoring results from National Park Service and tribal land managers in an iterative process to improve vegetation management outcomes.

4. Budget

Fiscal Year 2021								
Project C	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$114,700	$3,600	$2,000	$77,100	$116,800	$0	$31,100	**$345,300**

Fiscal Year 2022								
Project C	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$136,500	$3,900	$2,000	$79,300	$116,800	$0	$56,700	**$395,000**

Fiscal Year 2023								
Project C	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$140,600	$3,200	$2,000	$81,600	$110,900	$0	$67,000	**$405,000**

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

1. Investigators

Joel B. Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Helen Fairley, Social Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

This project is designed to provide quantifiable information about the effects of Glen Canyon Dam on archaeological sites and other diverse cultural resources embedded in the Colorado River ecosystem's (CRe) sediment-dependent riverine landscape. It will also help to inform decisions that may arise in the future as specific actions are proposed or implemented to protect and maintain cultural resources. According the Long-Term Experimental and Management Plan (LTEMP) Record of Decision (ROD) (DOI, 2016), the goal for archaeological sites and cultural resources is to "[m]aintain the integrity of potentially affected National Register of Historic Places (NRHP)-eligible or listed historic properties in place, where possible, with preservation methods employed on a site-specific basis." Additionally, there are other resource goals described in the LTEMP ROD that are directly tied to the goal for cultural resources, such as goals for tribal resources and sediment. For example, the goal for tribal resources is to "[m]aintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyon," while for sediment, the goal is to "[i]ncrease and retain fine sediment volume, area, and distribution in the Glen, Marble and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes." This project is designed to inform progress towards meeting each of these goals, as well as evaluating predictions about the anticipated effects of the preferred flow regime and other management actions, such as vegetation management, selected through the LTEMP Environmental Impact Statement (EIS) process. For example, the LTEMP ROD states that for cultural resources, the selected alternative (Alternative D) "will result in indirect potential benefits for archaeological sites in the Grand Canyon due to an increase in the availability of sand that will protect site stability… ." Project D is designed to quantitatively evaluate that predicted outcome. Moreover, the LTEMP ROD recommends to "[e]xplore vegetation management to benefit high value recreational beaches and protect vulnerable archaeological sites." Project D is designed to quantitatively evaluate the outcome of ongoing vegetation management for archaeological sites.

In addition to being responsive to LTEMP goals and predictions, this project is responsive to multiple legal and regulatory mandates. The Grand Canyon Protection Act (GCPA) specifically identifies cultural resources as one of the key resource categories that the law is intended to protect. Under GCPA, research and monitoring are required to determine whether the goals of protection, improvement, and/or effective mitigation of detrimental effects from Glen Canyon Dam operations are being achieved. The National Historic Preservation Act (NHPA) has somewhat similar obligations as GCPA.

To fulfill its compliance obligations under the NHPA, Reclamation has developed a Programmatic Agreement and a Historic Preservation Plan (HPP). The HPP is intended to guide future monitoring and mitigation activities, thereby fulfilling Reclamation's Section 106 compliance obligations related to the operation of Glen Canyon Dam and implementation of LTEMP. Among the commitments described in the HPP is an obligation to monitor dam effects using a variety of protocols, including the protocols described in the monitoring plan developed at the request of Reclamation by GCMRC in 2016 and implemented through Project Element D.1 (described below). Furthermore, as specified in the HPP, results from the GCMRC monitoring project will inform prioritization of future mitigation actions to be carried out under the HPP.

3. Proposed Work

Project Elements

Project Element D.1. Dam Operations, Vegetation Management, Archaeological Sites

[PI: Sankey, Co-PI: Fairley; Duration: FY 2021-23]

The purpose of this project element is to quantify changes in the physical condition of river corridor archaeological sites in Grand Canyon as a function of: (i) dam operations, (ii) vegetation management, and (iii) natural processes. Results of this project element, and its predecessors in previous workplans, are used to adaptively manage the CRe by:

- Determining whether increasing the frequency of High-Flow Experiments (HFEs) increases the resupply of river sand to archaeological sites in the river corridor and offsets erosion, thus achieving the LTEMP resource goal of "preservation in place."
- Determining if removal of riparian vegetation located between HFE-sediment supplied sand bars and archaeologic sites increases the probability of "preservation in place" and thus achieving the LTEMP resource goal.

There are more than 350 river corridor archaeological sites in Grand Canyon. Most sites are located in river sand deposits reworked by water, wind, and gravity. Most sites are eroding, and many are degraded specifically owing to gully erosion. However, river sand can help provide a

protective cover to preserve sites in place. Thus, the geomorphic condition of sites is affected by how Colorado River sand is transferred among landforms in Grand Canyon. The transfer of river sand from sandbar deposits to archaeological sites often occurs by wind in this ecosystem.

We use repeat ground-based light detection and ranging (lidar) surveys to measure changes in geomorphic condition of archaeological sites. We select sites for lidar measurements from the entire population of river corridor sites using two site classification systems that characterize the extent to which each site is: i) degraded by gully erosion, and ii) optimally positioned within the landscape to be resupplied with sand transferred from adjacent sandbars. At the completion of the FY 2018-20 Triennial Work Plan (TWP), the sample size of sites where lidar surveys have been conducted will be 30 sites. During the FY 2021-23 TWP we will revisit all 30 sites, conduct lidar surveys, quantify changes in geomorphic condition, and relate any changes that are detected to dam operations; specifically, we will relate changes to the occurrence and timing of HFEs.

In 2019, the National Park Service (NPS) implemented experimental vegetation removal treatments at five sites. The treatments were intended to increase the supply of sand to the sites. In 2020, the NPS will conduct maintenance at those sites to remove any vegetation regrowth and will conduct vegetation removal at one more site to bring the total number of treated sites to six. In this project, we will quantitatively evaluate the outcome and effectiveness of those vegetation management treatments. Lidar surveys acquired before and after the vegetation removal treatments provide baseline datasets from which we will determine whether sediment transfer occurs and increases at the sites as a function of the vegetation removals. We hypothesize that sediment transfer at the experiment sites will be greater under the combined effects of vegetation removal followed by an annual HFE. No HFE was conducted in 2019 and thus the first year of the experiment will provide insight to the effects of removing vegetation on sandbars that were not resupplied that year with sediment from an HFE. Future HFEs (e.g., if conducted in 2020 and/or 2021) will provide insight concerning effects of vegetation removal followed by an annual HFE.

Project Element D.2. Monitoring Landscape-scale Ecosystem Change with Repeat Photography

[PI: Fairley; Duration: FY 2021-23]

In the FY 2015-17 TWP, GCMRC initiated a project to monitor riparian vegetation change using repeat photography in collaboration with several tribal partners. Although the tribes later decided to discontinue their involvement, the initial results of this pilot photo matching effort proved to be highly informative and useful for a variety of GCMRC projects including Projects C and D in the FY 2018-20 workplan. Not only do the matched images visually document and illustrate the dramatic changes in river corridor vegetation, they also document the ongoing loss of open sand areas throughout the river corridor. The latter information is useful for reconstructing the pre-dam conditions under which archaeological sites and cultural landscapes existed prior to

emplacement of Glen Canyon Dam. Therefore, GCMRC continued a campaign to acquire matches of historical imagery in FY 2018-20, relying heavily on volunteer labor and focusing primarily on matching panoramic images of the riparian zone taken during the 1923 Birdseye expedition as well as the 1889-1890 Stanton expedition. All of the Stanton images and some of the Birdseye images were previously matched by USGS hydrologist Robert H. Webb and associates in the early 1990s, so the more recently acquired matches not only document changes in the riparian ecosystem since dam emplacement, they also document significant changes in riparian vegetation and open sand areas that have occurred since implementation of the modified low fluctuating flow regime in the mid-1990s.

In addition to matching images, in FY 2018-20 we collected information on species-level vegetation changes in each of approximately 200 locations throughout the river corridor with matched views; however, because the project was not funded in the FY 2018-20 TWP, and because we needed to rely on part-time unpaid labor to acquire the images and data, we have accumulated a large backlog of images and data that now need to be organized, analyzed, and ultimately published. In FY 2021, we propose to focus one staff member part time on analyzing and writing up the results of the past several years of work and publishing the results in a USGS monograph.

Over the course of this photo-matching effort, we have become aware of several other important photographic image collections that would be valuable to match for the benefit of multiple long-term monitoring programs in the CRe. One is a set of approximately 70 black-and-white images taken by Barry Goldwater during his 1940 river trip through Grand Canyon; the other is a set of images taken of recreational campsites along the Colorado River by Yates Borden and associates in 1973. The Goldwater images would be valuable to match because they were taken by a highly skilled photographer during a period of lower flows and lower magnitude floods than the Birdseye and Stanton images; therefore, they can provide a valuable comparison of pre-dam riparian vegetation conditions closer to the time of dam construction and under somewhat different flow conditions as compared to the those photographed in 1890 and 1923. The Goldwater images have never been matched by anyone, while the Borden images were matched imprecisely by student volunteers using low resolution point-and-shoot cameras approximately 15 years ago.

The Borden images are particularly valuable and worth replicating because they focus specifically on sandbar campsites and demonstrate the conditions at camping beaches less than 10 years after Glen Canyon Dam started regulating flows. As part of this project, we propose to create high quality, accurate matches of all these images to provide a visual record of decadal-scale ecosystem changes that can be used and analyzed by a variety of monitoring projects for years into the future. As in the past, matching of images will occur in conjunction with previously scheduled GCMRC research and monitoring trips to minimize cost; however, this

means that the project will need to extend over several years. Once the images and vegetation data have been acquired, they will be served to stakeholders and the public through GCMRC's website.

Project Element D.3. Cultural Program Administrative History

[PI: Fairley; Duration: FY 2021-22]

Project D builds on a multi-decadal legacy of research, monitoring, and adaptive learning that started more than 30 years ago when the Department of Interior decided to conduct a series of studies leading up to the 1995 Record of Decision for modifying operations of Glen Canyon Dam. Throughout the ensuing decades, representatives and scientists from the U.S. Geological Survey, Bureau of Reclamation, the National Park Service, and six traditionally affiliated tribes have produced numerous studies, reams of data, and, along with other stakeholders in the Glen Canyon Dam Adaptive Management Program (GCDAMP), they have individually and collectively influenced the directions and priorities of the GCDAMP cultural program in numerous ways. The complex and often contentious history of the GCDAMP cultural program is embedded in the memories of numerous living individuals, many of whom are still involved with the GCDAMP to this day. It is also reflected in numerous published and unpublished documents, many of which are no longer remembered or are unknown to newer members of the GCDAMP. After 30+ years of involvement in the GCDAMP, several key individuals are approaching or actively contemplating retirement. Before the knowledge and memories of these individuals disappears, it would be worthwhile for the GCDAMP to invest in recording a detailed administrative history specific to the cultural program of the GCDAMP.

For this project, we propose to assemble a comprehensive administrative history for the cultural resources monitoring and research programs of the GCDAMP (including tribal, archaeological, and geo-archaeological resources and their connections to other parts of the GCDAMP program). During the FY 2018-20 TWP, a synthesis and technical review of previous cultural resource research and monitoring work was prepared for use in developing the Historic Preservation Plan. The information assembled previously served its purpose to inform the HPP, but it was not written in a manner suitable for publication as a stand-alone public report. The proposed administrative history will draw on this previously assembled information, but it will include considerable additional historical information to capture the "who, when, what and why" components of the program. It will draw on the memories of all current participants in the cultural program, as well as those no longer active in the program who are willing to participate. The intent is to compile a detailed history that summarizes all previous work conducted in the cultural arena and the context in which that work occurred. It will take the form of a traditional administrative history document, with historical times lines and themes; however, oral history interviews, key documents, and other supporting materials will be made available through a supplementary web platform. The intent is to provide a published document that can serve as a useful reference for federal agencies and GCDAMP stakeholders, especially for new federal

employees and stakeholders who join the program in future years; it will also serve the interests of the general public. This project will greatly enhance and complement, but will not duplicate in any significant way, the GCDAMP administrative history project that is currently under development through a contract with Arizona State University.

Project Element D.4. Holocene Map of Fluvial Sediment in the Colorado River Corridor

[PI: Fairley; Duration: FY 2023]

To a large extent, the sedimentary deposits of the Colorado River corridor determine where suitable habitat for fish, vegetation, wildlife and other life forms are likely to occur. For similar reasons, having detailed knowledge of the age, type, and distribution of the sedimentary substrates in the river corridor is essential for determining not only where human beings formerly resided and farmed in the river corridor, but also where archaeological sites are likely to be buried or exposed by erosion in the future. As these deposits continue to erode over time due to operations of the dam and continuing depletion of the sediment supply in the river corridor, this map will help to guide managers in prioritizing future monitoring, treatment, and data recovery efforts.

As a planning and research tool, a comprehensive, detailed map of all Holocene fine sediment deposits and their approximate ages has been recommended to the GCDAMP for more than two decades. The Holocene deposits derived from the Colorado River are relatively easy to recognize and map at a gross level. As more archaeological and subsurface studies are conducted in the river corridor over time, these map units can be further refined and split into smaller units. For this project, we propose to begin the process of developing a corridor-wide base map of fluvial and aeolian deposits originating from the Colorado River by drawing on prior work of USGS researchers (e.g., East, Fairley, Grams, Hereford, Lucchitta, Topping, and others) as well as outside academic researchers such as V. Baker and J. Pederson. Existing data will be transferred to a corridor base map and field checked. In future years, these existing data will be supplemented with additional fieldwork to fill in coverage gaps where necessary. Ultimately, all of these data will be compiled in a Geographic Information System in the form of a digital map that can be edited and refined in the future as additional work in the river corridor continues and improves current understanding. For this first year of the project, the focus will be on compiling existing data from multiple published and unpublished sources.

4. Budget

Fiscal Year 2021								
Project D	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$266,700	$11,800	$7,800	$19,500	$0	$0	$42,800	**$348,600**

Fiscal Year 2022								
Project D	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$248,400	$11,800	$9,300	$20,100	$0	$0	$69,500	**$359,100**

Fiscal Year 2023								
Project D	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$242,300	$11,400	$9,400	$20,800	$0	$0	$79,500	**$363,300**

5. References

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Project E. Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature

1. Investigators

Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Bridget Deemer, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Kimberly Dibble, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Theodore Kennedy, Research Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Michael Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Robert Hall, Professor, Flathead Lake Biological Station, University of Montana
Daniel Buscombe, Assistant Research Professor, Northern Arizona University

2. Project Summary and Purpose

Aquatic primary production is an important energy source for riverine food webs, converting sunlight, carbon dioxide and water into simple carbohydrates via photosynthesis. In the Colorado River downriver of Glen Canyon Dam, fish are food limited (Cross and others, 2011) and energy (carbon) produced within the river is a preferred food source relative to energy from tributaries and riparian inputs (Wellard Kelly and others, 2013). Aquatic primary production, and the aquatic insect community this production supports, is the main source of fish production in Glen Canyon throughout the year (Cross and others, 2011). Primary producers (specifically diatoms) are also a preferred food source downstream, although the role of non-algal (tributary/terrestrial) carbon sources can also be an important driver of the food availability during flood pulses such as occur during monsoon season (Cross and others, 2011; Wellard Kelly and others, 2013; Sabo and others, 2018).

There are several lines of evidence that link both nutrient concentrations and primary productivity to higher trophic levels throughout the Colorado River. Outside of periods when tributaries are flooding for extended periods, the availability of aquatic insect drift and the condition of native fish are positively related to seasonal rates of gross primary production near the Little Colorado River, highlighting the important role for aquatic primary production even 120 km downstream of the dam (Deemer and others, 2020 annual reporting). Primary production at Diamond Creek also appears linked to juvenile production of flannelmouth suckers, the most common species in this area, further highlighting the importance of in situ production to fish

communities in the western canyon. While total primary production is not significantly related to metrics of fish production in Glen Canyon, the availability of phosphorus, an important limiting nutrient, is correlated with chlorophyll *a*, a metric of diatom and other non-macrophyte-based primary production. Furthermore, phosphorous predicts rainbow trout recruitment better than flow-based metrics used to predict recruitment for the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) (Yackulic and others, 2020 annual reporting).

Understanding the controls on Colorado River primary production is an important step towards better managing the aquatic food base. Disentangling the drivers of both rates and types of riverine primary production and their link back to fish production, is particularly challenging given interactive and delayed effects and given different levels of information on the potential drivers. For example, monsoonal storm pulses that place temporary light availability constraints on rates of primary production (Hall and others, 2015) may also be delivering significant amounts of phosphorus to the mainstem. In a second example, at times of high phosphorus outflow from Glen Canyon Dam, elevated production of a dominant food source, diatoms, may suppress macrophyte production (via shading) obscuring the link between overall productivity and higher trophic levels.

This project aims to disentangle some of these drivers by combining the highly resolved long-term information about riverine turbidity, silt and clay concentrations, solar inputs, discharge, and gross primary productivity (via continuous oxygen and temperature measurements – data that are collected as parts of the Lake Powell project, Project A, and Project E) with improved additional information about phosphorus, gas transfer, ecosystem respiration, and the relative role of diatoms in affecting whole river production (Elements E.1 and E.2). Elements E.1 and E.2 are designed to capture and link changes in productivity to changes in bottom-up drivers such as light, flow, and nutrients and to further develop links between these bottom up drivers and higher trophic levels.

Another goal for this project is to consider how primary productivity is meeting (or not meeting) fish metabolic demands (Element E.3). This will involve laboratory work that quantifies the basal and active metabolism of native fish (humpback chub and flannelmouth suckers). Past bioenergetics work done in the 2000s (Petersen and Paukert, 2005; Paukert and Peterson, 2007) assumed humpback chub had a metabolism like other *Gila spp.* because it has never been directly measured in humpback chub. However, observations from previous lab work and the response to lowered food in the mainstem Colorado River suggest that humpback chub may have abnormally low metabolisms that enable them to persist through periods of food shortage. By estimating these basal metabolisms and absolute fish population abundances for Colorado River reaches, we can determine how much carbon (i.e., energy) is being consumed and how this relates to the amount of carbon produced by primary production. This work will also use discrete estimates of ecosystem respiration (Element E.2) to constrain the fraction of gross primary production that we expect is available to pass to higher trophic levels (e.g. net primary

production). We will use the information and data collected through various projects to develop aquatic ecosystem models that consider trophic linkages. During FY 2021-23, we will continue efforts to link river-wide primary productivity with bottom-up drivers, with the goal of understanding how physical and chemical conditions are regulating the Colorado River food web. Additional new work will focus on quantifying the metabolic demand of native fish so that energy in (via primary production) can be better related to fish production.

3. Proposed Work

Project Elements

Project Element E.1. Phosphorus Budgeting in the Colorado River

Identify the relative importance of different phosphorus sources to the productivity of the Colorado River system

This project will expand current monitoring of tributary Phosphorus (P) inputs and mainstem P cycling by combining USGS automated water samplers with a citizen science-based nutrient sampling program and targeted sediment incubations. Specifically, we will conduct storm-based sampling of the Paria and Little Colorado Rivers using automated water sampling, citizen science-based water sampling in both the Colorado River mainstem and its tributaries, and bio-assays of river sediments. Water samples will be analyzed for various species of P, as well as other constituents that may alter the cycling of P. Bio-assay will help us better understand how P is retained and released by sediments in the river. Taken together, these activities will help us to construct an overall P budget for the Colorado River and will help us to determine how P is linked to gross primary productivity (especially in further downriver sections where tributary inputs potentially override the influence of variation in the SRP in dam releases) via modeling in element E.2.

Project Element E.2. Rates and Composition of Primary Producers in the Colorado River

Identify patterns and controls on primary productivity in the Colorado River

We will continue dissolved oxygen monitoring and modeling and efforts to document the changing makeup of the aquatic primary producer community in Glen Canyon. Dissolved oxygen monitoring occurs through sampling at fixed gage sites by project A, and through sampling at a variety of other sites by project E, including both continuous sampling in Glen Canyon and seasonal sampling throughout the Colorado River. We plan targeted efforts to better constrain gas exchange rates (particularly in the western Grand Canyon where relationships described in Hall and others, 2012 between elevation loss and exchange do not apply). Modeling will continue to focus on determining the relative importance of phosphorous, flow, temperature and other factors (e.g., turbidity) on rates of primary production – taking advantage of improved understanding of the P-budget through element E.1, as well as flow experiments planned for this

time period. In 2022, we plan to repeat map the vegetation in Glen Canyon. In addition, we plan to determine the proportion of primary production in Glen Canyon that is derived from diatoms, as opposed to macrophytes.

Project Element E.3. Productivity at Higher Trophic Levels

Fish metabolism and ecosystem modeling

We will combine absolute fish population abundances estimated from fixed sites (i.e., in Glen Canyon, JCM, and JCM-west – see projects G and H), invertebrate drift data (project F) with a better understanding of primary production (Element E.2) and lab measures of fish basal metabolism to develop ecosystem models. Lab experiments will be used to determine metabolism of the two species of native fish (humpback chub and flannelmouth sucker) that dominate the biomass of fish communities for which there are no literature values. These data will be integrated into aquatic ecosystem modeling that seeks to understand dynamics of fish communities throughout different reaches of the Grand Canyon from an energetic perspective. This modeling will integrate primary productivity data, insect drift data, and fish growth and population size data to understand trophic linkages and better predict how the system will respond to changes in nutrients, temperature and flow.

4. Budget

Fiscal Year 2021								
Project E	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$ 342,723	$ 8,400	$ 35,500	$ 6,400	$ 31,800	$ -	$ 55,977	**$480,800**

Fiscal Year 2022								
Project E	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$ 336,715	$ 10,500	$ 30,000	$ 3,150	$ 26,800	$ -	$ 92,092	**$499,257**

Fiscal Year 2023								
Project E	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$ 348,188	$ 10,500	$ 15,000	$ 2,500	$ 26,800	$ -	$ 106,137	**$509,125**

5. References

Cross, W.F., Baxter, C.V., Donner, K.C., Rosi-Marshall, E.J., Kennedy, T.A., Hall, R.O., Jr., Wellard-Kelly, H.A., and Rogers, R.S., 2011, Ecosystem ecology meets adaptive management—Food web response to a controlled flood on the Colorado River, Glen Canyon: Ecological Applications, v. 21, no. 6, p. 2016-2033, https://doi.org/10.1890/10-1719.1.

Deemer, B.R., 2020, Lake Powell as a regulator of downstream water quality and ecosystem productivity—presentation: Phoenix, Ariz., U.S. Geological Survey, Glen Canyon Dam Adaptive Management Program annual reporting meeting, January 13, 2020, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-LakePowellRegulatorDownstreamWaterQualityEcosystemProductivity-Presentation-508-UCRO.pdf

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

Paukert, C.P., and Petersen, J.H., 2007, Comparative growth and consumption potential of rainbow trout and humpback chub in the Colorado River, Grand Canyon, Arizona, under different temperature scenarios: The Southwestern Naturalist, v. 52, no. 2, p. 234-242, https://doi.org/10.1894/0038-4909(2007)52[234:CGACPO]2.0.CO;2.

Petersen, J.H., and Paukert, C.P., 2005, Development of a bioenergetics model for humpback chub and evaluation of water temperature changes in the Grand Canyon, Colorado River: Transactions of the American Fisheries Society, v. 134, no. 4, p. 960-974, https://doi.org/10.1577/T04-090.1.

Sabo, J.L., Caron, M., Doucett, R.R., Dibble, K.L., Ruhi, A., Marks, J.C., Hungate, B.A., and Kennedy, T.A., 2018, Pulsed flows, tributary inputs, and food web structure in a highly regulated river: Journal of Applied Ecology, v. 55, no. 4, p. 1884-1895, https://doi.org/10.1111/1365-2664.13109.

Yackulic, C.B., 2020, Predictions, populations, and energetic constraints—presentation: Phoenix, Ariz., U.S. Geological Survey, Glen Canyon Dam Adaptive Management Program annual reporting meeting, January 13, 2020, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-PredictionsPopulationsEnergeticConstraints-Presentation-508-UCRO.pdf.

Wellard Kelly, H.A., Rosi-Marshall, E.J., Kennedy, T.A., Hall, R.O., Jr., Cross, W.F., and Baxter, C.V., 2013, Macroinvertebrate diets reflect tributary inputs and turbidity-driven changes in food availability in the Colorado River downstream of Glen Canyon Dam: Freshwater Science, v. 32, no. 2, p. 397-410, http://dx.doi.org/10.1899/12-088.1.

Project F: Aquatic Invertebrate Ecology

1. Investigators

Theodore A. Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Jeffrey D. Muehlbauer, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

The focus of Project F is continuation of long-term monitoring needed to track ecosystem response to "Bug Flows" and other Long-Term Experimental and Management Plan (LTEMP) flow experiments. Research by our group has demonstrated that the scarcity of mayflies, stoneflies, and caddisflies from the Colorado River is partly due to acute mortality of insect eggs arising from hourly changes in discharge associated with hydropower generation. In May-August of 2018 and 2019, Glen Canyon Dam operations were experimentally modified to increase the production and diversity of aquatic insects in the Colorado River in Grand Canyon (Arizona, USA). These experimental Bug Flows involved hourly flow fluctuations for hydropower generation during weekdays, coupled with steady, low flows on weekends to reduce aquatic insect egg desiccation and mortality. We are tracking ecosystem response to the Bug Flow experiment using citizen science monitoring of aquatic insects (2012-present), monitoring of invertebrate drift (2008-present), fish diet studies (sporadic), and other standardized monitoring approaches. Multiple monitoring metrics indicated a strong and positive food base response in 2018 followed by a decline back to baseline values in 2019. However, interpretation of these Bug Flow data is complicated by a large increase in tributary flooding and suspended sediment loading to the Colorado River in winter-spring of 2019 relative to prior years (2012-2018); high levels of suspended sediment can be a major constraint on growth and production of aquatic insects. Additional years of Bug Flow testing in FY 2021-23 would likely be useful in quantifying the extent to which this cost-effective mitigation strategy increases the abundance and diversity of the food base in Glen and Grand Canyon.

3. Proposed Work

Project Elements

Project Element F.1. Aquatic Invertebrate Monitoring in Marble and Grand Canyons

This element focuses on identifying links between Glen Canyon Dam operations and the aquatic food base. We focus our efforts on invertebrate drift and insect emergence because they can be used to make inferences about the health and status of invertebrate populations, and they also provide a direct measure of the food base available to humpback chub (*Gila cypha*),

flannelmouth sucker (*Catostomus latipinnis*), rainbow trout (*Oncorhynchus mykiss*), and other wildlife populations (see Projects G and H, especially). This represents the core monitoring effort for evaluating the efficacy of Bug Flows, High-Flow Experiments (HFEs), and other experimental dam operations that might affect the aquatic food base. We will continue citizen science monitoring of adult aquatic insects using light traps, which has been ongoing since 2012. We will also continue monitoring aquatic insect larvae by collecting drift samples in the Colorado River every ~3 miles during river trips in spring, which started in 2017 prior to Bug Flows.

Project Element F.2. Aquatic Invertebrate Monitoring in Glen Canyon

This element is a continuation of a monthly Glen Canyon monitoring program that has been ongoing since 2007, representing a valuable long-term dataset for identifying status and trends in the aquatic food base supporting rainbow trout populations. Invertebrate drift is sampled monthly at eight sites from Glen Canyon Dam (River Mile -16) to the head of Badger Rapid (River Mile 8), which allows us to understand and model changes in invertebrate drift over time and also in response to flow conditions such as riffles, pools, and tributary sediment inputs from the Paria River. Adult aquatic insects are also monitored on these trips using sticky and light traps.

Project Element F.3. Aquatic Invertebrate Monitoring of Grand Canyon Tributaries

This element involves monitoring the aquatic invertebrate community within tributary streams in Grand Canyon. These streams are important spawning and rearing habitat for native fish and sources of aquatic insects that could recolonize the mainstem Colorado River. We will continue monitoring the aquatic food base in Bright Angel Creek, which started in 2013 prior to nonnative trout removal efforts. Data collected to date have shown that ongoing trout removal efforts have led to strong aquatic community shifts, with implications for the food base available to humpback chub that were reintroduced to the Creek starting in 2018. We will also process samples collected from 16 tributaries throughout Marble and Grand Canyons in 2014, and we will repeat sampling of these same tributaries in 2023. These two sample sets (2014 and 2023) will allow us to quantify the diversity of aquatic invertebrates throughout Grand Canyon tributaries, something that was last assessed in 1996. This information will be used to determine if tributaries harbor enough insect diversity to potentially re-colonize the mainstem Colorado River in Grand Canyon, or whether repatriation of native mayflies, stoneflies, and caddisflies from other segments of the Colorado River might be warranted.

Project Element F.4. Fish Diet Studies

This element focuses on quantifying the feeding habits of rainbow trout in Glen Canyon and native fish in Grand Canyon. We will synthesize rainbow trout diet data collected during 2018-2020 to determine the extent to which the quantity and quality of food consumed differs between steady, low weekend Bug Flows and regular, fluctuating weekday flows. We will also assess the feeding habits of humpback chub and other native fish in the mainstem Colorado River near the

Little Colorado River confluence and Fall Canyon (see project G). Native fish feeding habits in the mainstem Colorado River were last rigorously assessed in the mid-2000s. Combined, this information will elucidate the extent to which Bug Flows may be affecting the food base available to rainbow trout and native fish and may help explain recent native fish population increases in western Grand Canyon.

Project Element F.5. Spring Powerplant Capacity Flow (Experimental Fund)

This element focuses on quantifying food base response to potential flow experiments being considered by the FLows Ad Hoc Working Group (FLAHG). The March 2008 Spring HFE appeared to stimulate the aquatic food base by scouring senescent algae and reducing the abundance of New Zealand mudsnails. The food base that re-colonized the Colorado River in the months following the 2008 HFE was dominated by fast-growing, nutritious algae and fast-growing aquatic insect species including midges and blackflies. In contrast, recent fall HFEs from 2012-2018 appear to have had neutral-to-negative impacts on the food base by potentially facilitating expansion of aquatic macrophytes and increasing abundance of New Zealand mudsnails. Analysis of Paria River discharge data indicate sediment-triggered spring HFEs are increasingly unlikely owing to reductions in the frequency and intensity of winter storms. Therefore, the FLAHG has been evaluating whether it is possible to experiment with spring-timed flow disturbances that are not sediment triggered. This element includes funding for tracking food base response to these potential flow experiments including comprehensive benthic sampling and small-scale habitat manipulations (e.g., pressure-washing cobble bars) that will complement a larger, ecosystem-scale flow experiment if that occurs.

4. Budget

Fiscal Year 2021								
Project F	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS	Burden 14.000%	Total
Budgeted Amount	$616,000	$31,000	$28,000	$24,000			$98,000	**$797,000**
Fiscal Year 2022								
Project F	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS	Burden 24.000%	Total
Budgeted Amount	$570,000	$28,000	$29,000	$24,000			$156,000	**$807,000**
Fiscal Year 2023								
Project F	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS	Burden 28.000%	Total
Budgeted Amount	$534,000	$27,000	$29,000	$51,000			$179,000	**$820,000**

5. Budget for Experimental Fund Proposal (F.5.)

Fiscal Year 2021								
Project F5	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS	Burden 14.000%	Total
Budgeted Amount	$102,000	$19,000	$1,000	$0			$17,000	**$139,000**

Project G: Humpback Chub Population Dynamics throughout the Colorado River Ecosystem

1. Investigators

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Kirk Young, Assistant Project Leader, U.S. Fish and Wildlife Service
Michael Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service
David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Tennant, Fish Biologist, U.S. Geological Survey Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

During FY 2021-23, we will continue monitoring activities mandated by the Biological Opinion (BiOp) associated with the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS), while focusing research on improving our understanding of the abundance and drivers of humpback chub population dynamics. Research will focus on understanding drivers of juvenile production, estimating survival and growth around the Little Colorado River (LCR) and in western Grand Canyon, and determining the overall adult abundance in the western Grand Canyon.

Juvenile production in the LCR since 2012 has not been sufficient to maintain the current size of the adult population that spawns in the LCR and we expect a decline in adult populations over the next few years. It is unclear if lowered juvenile production is indicative of a trend, suggesting need for additional management actions, or a component of natural variability. During FY 2021-23, we will continue to estimate juvenile production and test hypotheses regarding drivers of juvenile production. We will also continue to resolve our understanding of how rainbow trout, temperature, turbidity, and food limitation drive growth, survival, and fish condition in the mainstem Colorado River.

Humpback chub catch in the Western Grand Canyon has been increasing steadily since 2014, however a closer look suggests that these increases are primarily driven by a few years of high juvenile production. We lack a basic understanding of the drivers of survival, growth, juvenile

production, and reach-wide adult abundance. During FY 2021-23, we will test various hypotheses regarding the drivers of juvenile production using existing data, gather further juvenile chub data in western Grand Canyon that will allow us to model growth and survival, and integrate existing data to develop an estimate of abundance in this expanding population segment.

To satisfy the BiOp, test hypotheses about drivers, and estimate adult abundance, we propose to monitor humpback chub in the LCR-spawning population by sampling the LCR and juvenile chub monitoring (JCM-east) reach in the Colorado River (Project Elements G.2, G.3), and in the western Grand Canyon population via continuation of mark-recapture in the Fall Canyon reach (JCM-west) and extensive sampling via the aggregation and seining trips (Project Elements G.5, G.6, G.8). Mark-recapture data from these trips will be supplemented with data from autonomous passive integrated transponder (PIT) tag antennas, such as the LCR multiplexer array (MUX) and submersible antennas, as these technologies have proven effective at detecting larger adults which are often difficult to capture using other methods such as hoop netting and electrofishing (Project element G.4). Lastly, since models developed under the previous workplan suggest that Chute Falls translocations do help augment the LCR-spawning adult population, the workplan proposes continuation of Chute Falls translocations and monitoring by the U.S. Fish and Wildlife Service (USFWS: Project Element G.7). We also propose to analyze otoliths from incidental mortalities of age-0 fish collected over the last few years in the LCR to get a better understanding of hatch dates, which may in turn help us understand the degree to which LCR hydrology affects juvenile production. Data collected from the above-mentioned field efforts will be analyzed to help learn more about humpback chub life history and to guide management efforts (Project Element G.1).

3. Proposed Work

Project Elements

Project Element G.1. Humpback Chub Population Monitoring

Evaluate population dynamics using mark-recapture data

Models will use data from field sampling to help inform management efforts for humpback chub. Proposed projects include: 1) estimating abundance of various size classes in the LCR-spawning population for the BiOp, 2) assessing drivers of age-0 production and outmigration in the LCR-spawning population, 3) evaluating population dynamics in the Fall Canyon reach (part of the western Grand Canyon population), and 4) estimating abundance of the entire western Grand Canyon population by evaluating covariate (e.g., flow, temperature) effects on capture probability, which would enable estimation of abundance from catch data.

Project Element G.2. Annual Spring/Fall Abundance Estimates of Humpback Chub in the Lower 13.6 km of the LCR

USFWS sampling trips

The USFWS has been conducting four sampling trips into the LCR each year since 2001, and this data set is used to estimate humpback chub abundance at different life stages. These abundance estimates document substantial temporal changes to adult population size since 2000, most notable of which is the increase in adult abundance that has occurred since 2007. This project element will continue into the next workplan to help assess the health of the LCR-spawning humpback chub population and to inform potential management actions, such as the triggers for trout removal.

Project Element G.3. Juvenile Chub Monitoring near the LCR Confluence (JCM-east)

Sampling trips to the JCM-east reach and lower LCR

This project element is a continuation of previous monitoring work that commenced in 2012 and includes three annual sampling trips to the JCM-east reach as well as one annual sampling trip to the lower LCR. Data from these trips provide information about age-0 production in the LCR, age-0 outmigration to the JCM reach, and life-stage specific abundance estimates from the Colorado River and LCR. These life-stage specific estimates can help predict future changes to adult humpback chub population size.

Project Element G.4. Remote PIT Tag Array Monitoring in the LCR

Assessing humpback chub movement and improving detection of large fish

Previous work suggests that models fit to mark-recapture data from physical captures (i.e., mainly hoop nets and electrofishing) underestimate survival and movement probabilities compared to models that include both data from physical captures and autonomous PIT tag antenna detections. This project element would fund maintenance of two stationary antenna systems, a multiplexer array and a network of shore-based single antennas located within the LCR.

Project Element G.5. Monitoring Humpback Chub Aggregation Relative Abundance and Distribution

Canyon-wide sampling of fish throughout Grand Canyon with an emphasis on humpback chub

Compared to JCM-east and JCM-west sampling, humpback chub aggregations trips sample fish less intensively, but over a wider spatial area that encompasses all of Marble Canyon and Grand Canyon. These sampling efforts visit sites throughout this system. Humpback chub aggregations sampling will include one or two sampling trip(s) per year to visit aggregations sites and some non-aggregation sites to help assess how temporal patterns in abundance vary spatially.

Project Element G.6. Juvenile Humpback Chub Monitoring in Western Grand Canyon (JCM-West)

Sampling fish in Fall Canyon reach to learn more about survival, abundance, and growth

USGS established a fixed monitoring site in western Grand Canyon, Fall Canyon reach, JCM-west, in fall 2017. This site is visited three times each year, typically in May, July, and October. We propose to continue monitoring fish in Fall Canyon reach, as estimates from this reach will serve as an index for the entire western Grand Canyon population.

Project Element G.7. Chute Falls Translocations

Management and monitoring to increase humpback chub adult abundance in the LCR-spawning population

Models developed under the FY 2018-20 Triennial Work Plan suggest that humpback chub translocated above Chute Falls experience fast growth and high survival and that Chute Falls translocations are a beneficial management tool for increasing abundance of humpback chub. Specifically, the results of the model predict that translocating 300 age-0 humpback chub each year above Chute Falls will result in having an extra 350 adults compared to not doing the translocation. Accordingly, under this workplan we propose to continue Chute Falls translocations and monitoring. This requires adding one additional camp (3-4 people) during the May USFWS sampling trip for monitoring work, and additional people and helicopter time during the October trip to catch and translocate fish from the lower LCR to above Chute Falls.

Project Element G.8. Backwater Seining

Canyon-wide sampling of fish throughout Grand Canyon with an emphasis on age-0 fish, particularly humpback chub

This trip samples backwater habitat throughout Grand Canyon using seining, a method that is effective at capturing age-0 humpback chub. Data from this trip provides an index of humpback chub age-0 production throughout the mainstem Colorado River.

Project Element G.9. Assessing Yearly Variability in Humpback Chub Hatch Dates

Evaluation of humpback chub otoliths (from incidental mortalities) to determine hatch dates and age-0 growth in the Little Colorado River

Humpback chub life history is hypothesized to be strongly linked to hydrological cues. In the LCR, abundance estimates and mean sizes of age-0 chub in July show high variability from year to year, but little is known if, or how, this variability relates to flow and temperature conditions. Analysis of age-0 humpback chub otoliths would allow for determination of hatch date distributions and provide estimates of age-0 growth. All otoliths used in this project element could come from incidental mortalities (i.e., fish that previously died accidentally during sampling).

4. Budget

Fiscal Year 2021								
Project G	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$ 389,264	$ 4,000	$ 74,750	$ 636,341	$ 506,266	$ -	$ 169,798	**$1,780,418**

Fiscal Year 2022								
Project G	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$ 404,192	$ 4,000	$ 82,250	$ 711,707	$ 506,266	$ -	$ 303,704	**$2,012,119**

Fiscal Year 2023								
Project G	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$ 371,095	$ 4,000	$ 69,750	$ 675,566	$ 506,266	$ -	$ 328,903	**$1,955,580**

Project H: Humpback Salmonid Research and Monitoring Project

1. Investigators

Kimberly Dibble, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Michael Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Josh Korman, Fish Biologist, President, Ecometric Research Inc., Vancouver, Canada
Laura Tenant, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
David Rogowski, Fish Biologist, Arizona Game and Fish Department
Clay Nelson, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Molly A.H. Webb, Bozeman Fish Technology Center, U.S. Fish and Wildlife
James A. Crossman, Fish Ecologist, BC Hydro, Vancouver, Canada

2. Project Summary

The Long-Term Experimental and Management Plan (LTEMP) (DOI, 2016) provides the necessary long-term framework for assessing specific operations at Glen Canyon Dam, as well as other types of management actions conceived and implemented over the 20-year LTEMP period. For this reason, the Salmonid Research and Monitoring Project was developed with the long view; particularly being able to respond to unanticipated and emerging risks (e.g., brown trout). Experimental flows were designed to limit rainbow trout recruitment and dispersal out of Lees Ferry with a goal of maintaining the balance between the sport fishery and the humpback chub population downstream. However, ecosystems are dynamic, and there has been a large increase in brown trout recruitment upstream of Lees Ferry over the past few years (2015-2019) (Runge and others, 2018). Given this new development, it is unclear whether the expansion of brown trout will disrupt the balance between salmonids and endangered native fish downstream, the rainbow trout fishery in Glen Canyon, and the degree to which flow manipulations can be used to manage rainbow and brown trout.

The study design described in the FY 2018-20 Triennial Work Plan (TWP) is still relevant for addressing the same management questions posed in the LTEMP, and likely other workplans developed in the future. As such, this type of experimental approach is appropriate for understanding large and complex ecosystems, particularly when quantifying rainbow trout and brown trout population dynamics. This research project proposes to evaluate: 1) the effect of

trout management flows (TMFs) on recruitment and dispersal, 2) the effects of spring and fall High-Flow events (HFEs) on trout recruitment, dispersal, and growth, 3) factors controlling trout recruitment and dispersal into Marble Canyon and Little Colorado River (LCR) reaches, 4) factors controlling the quality of the trout fishery (growth and sexual maturity), 5) factors responsible for seasonal difference in catch vulnerability of juvenile brown trout, and 6) factors regulating brown trout population dynamics, early life history stages, as well as efficacy of an incentivized harvest program of larger sized brown trout. Summarized below are monitoring and research elements that address the primary study objectives.

3. Proposed Work: Ongoing Monitoring Studies

Project Elements

Project Element H.1. Rainbow Trout Monitoring in Glen Canyon

The objective of this project element is to monitor the basic fish population characteristics, including relative abundance, size composition, distribution, and recruitment of rainbow trout and brown trout. The current monitoring program is designed to be able to detect population level changes over a five-year time scale. Additionally, the Lees Ferry Creel Survey and Arizona Game and Fish Department (AZGFD) Citizen Science Project (FY 2018-20 TWP), which evaluates the quality and changes in the recreational experience of angling in the rainbow trout fishery in the Lees Ferry, Glen Canyon National Recreation Area (Rogers, 2015) is proposed to be continued. Currently, estimates of angler catch quality (i.e., number of fish ≥ 14" and fish ≥ 20") cannot be reliably determined from these surveys without substantive bias; therefore, AZGFD has been conducting a citizen science project that utilizes fishing guides to collect length data on fish caught by their clients.

4. Proposed Work: New and Continuing Research Studies

Project Elements

Project Element H.2. TRGD Fieldwork

The research project referred to as the Trout Reproductive and Growth Dynamics (TRGD, Project Elements H.2) is designed to determine the effects of LTEMP ROD flows on the recruitment of young-of-year (YOY) trout (rainbow trout and brown trout) in Glen Canyon, trout growth rates of juveniles and adults, and dispersal of YOY trout from Glen Canyon to Marble Canyon. Another central objective of TRGD is to increase our understanding of the key factors (trout density and recruitment, prey availability, nutrients, etc.) that control abundance and growth of the Glen Canyon trout population(s). This improved understanding could lead to the identification of policies other than flow manipulation that could benefit the Lees Ferry fishery and limit the downstream dispersal of rainbow trout to the LCR, as well as controlling brown trout numbers should this species become even more established in Glen Canyon (Runge and

others, 2018). For purposes of study replication, a multi-reach mark-recapture sampling design was established having three sub-reaches, each with an assigned 3-km length (sum 36% areal coverage). Spatial coverage allows for the replication necessary for assessing experimental flow effects, and unlike the upper and middle two sub-reaches, the lowest sub-reach (1C) has been sampled since 2012, which allows the TRGD program to maintain continuity with past data collection efforts, and the necessary long-term analysis (comparisons and contrasts) associated with the Natal Origin project (2012-2017; FY 2015-17 TWP, Project Elements 9.1, 9.2, and FY 2018-20 TWP). These data are then used independently to inform: 1) the spatially stratified open population model for rainbow trout (Korman and others, 2017a, b), and 2) the population model for brown trout (Runge and others, 2018; Yackulic, 2020). TMFs, and Spring Power Plant Capacity Flows are key elements of the LTEMP EIS and are intended to reduce large recruitment events by trout in Glen Canyon to limit downstream dispersal, but perhaps more importantly to avoid the persistence and expansion of a growing brown trout population (Petty, 2019).

1. Comparing vital rate trends in trout populations between summer months in years when TMFs are conducted, and between fall months or spring months in years when fall- or spring-HFEs are conducted, provides a rigorous evaluation of TMF and HFE effects (that will be replicated in all three reaches).

2. Since TMFs may be implemented if conditions warrant, there are some critical information needs (literature review on fish stranding) required before TMFs are tested. The TRGD quarterly sampling design provides the larger quantitative framework; however, additional supplemental field studies are needed to further assess trout early life stages (TELS) should TMFs, Spring Power Plant Capacity Flows, or other alternative flow scenarios be implemented to strand YOY trout during the FY 2021-23 period. That is, data from both field efforts will be used to provide estimates of how these experimental flows influence survival and recruitment of early YOY, as well as other size-classes of trout (compensatory response in the population). To minimize project costs, the TELS component is proposed to be funded from the Experimental Fund during years when TMFs or alternative flows are implemented.

3. Condition factor is higher when growth is higher, potentially leading to an increase in the proportion of trout that reach sexual maturity and spawn. Preliminary data from the FY 2018-20 TRGD project shows that annual recruitment is well predicted by condition factor from the previous fall and growth rates for small trout in the year of recruitment. Thus, condition-affected sexual maturation rate appears to play an important role in regulating annual recruitment. Understanding the relationship between condition-affected sexual maturation and recruitment may help us develop a more reliable method for forecasting and response to large recruitment events (H.4).

4. Trout dispersal out of Glen Canyon as well as trout population dynamics will continue to be monitored in Marble Canyon and near the LCR confluence in conjunction with humpback chub monitoring (Project Element H.1, Project G).

5. Monitoring population dynamics of brown trout provides the means to assess incentivized take harvest measures by National Park Service (Project Element J.2).

Project Element H.3. Brown Trout Early Life History Stages in Glen Canyon

The brown trout early life stage (BTELS) study objectives are to identify the early life history stages in which brown trout are: 1) vulnerable to flow manipulation, 2) using near-shoreline habitat, and 3) physiologically affected by experimental flows (flow duration and timing). This project focuses on early life history stages of brown trout that are often too developmentally small to be captured using conventional sampling methods (Project Elements H.2). Typically, brown trout spawn over a three-month period (November-January) in advance of rainbow trout (March-April). It follows that the early life history stages (hatch and swim-up dates) of YOY brown trout (<75 mm FL) should precede those of rainbow trout. Although a spawning offset exists between the two trout species, YOY rainbow trout (size range 35-60 mm FL) are detected along the shoreline during the June/July sampling effort. Yet, few if any young brown trout are detected prior to or during the same TRGD sampling effort as would be expected based on their earlier spawning time. Instead, juvenile brown trout are readily caught in the September and October sampling trips at sizes much larger than are observed for young rainbow trout.

Differences in sizes at capture between trout species suggest that brown trout YOY are not occupying the near shoreline (wetted edge) when smaller in size. If brown trout YOY are using different habitat at smaller sizes (<75 mm fork length; FL), they are not likely to be as affected by TMFs, particularly in the spring. Therefore, BTELS is proposed to be conducted monthly (January-April) to quantify brown trout YOY densities and apparent monthly survival rates. In this project YOY otoliths will be used to examine: 1) vital rates of early life stages of brown trout to inform recruitment models (Project Elements H.4), 2) brown trout hatch and emergence dates to inform the timing of experimental flows (Project Elements H.2), and 3) the physiological response of brown trout to HFEs and TMFs, including variations in responses due to flow timing and duration. Results will identify when brown trout are most vulnerable to flow manipulation and if there are habitat use differences between trout species. Otoliths are to be collected and removed from a sample of preserved fish to determine the daily age from hatch date and incremental daily growth (Korman and Campana, 2009).

Project Element H.4. Salmonid Modeling

Salmonid modeling priorities in this workplan include: 1) estimating the efficacy of incentivized harvest on brown trout to inform managers and for Project J by updating the brown trout population model and incorporating harvest data, 2) reassessing the hypotheses explored in

Runge and others (2018) using data collected in recent years, 3) estimating population dynamics of rainbow trout in the Lees Ferry reach in response to experimental flows, and 4) continuing to develop models to predict recruitment and outmigration of rainbow trout. Outmigration of rainbow trout from Lees Ferry to downstream areas, particularly near the LCR confluence, is seen as detrimental to native fish conservation goals (Yackulic and others, 2018).

5. Budget

Fiscal Year 2021								
Project H	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$ 263,977	$ 16,304	$ 43,516	$ 242,070	$ 178,000	$ -	$ 84,561	**$828,428**

Fiscal Year 2022								
Project H	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$ 230,787	$ 5,000	$ 45,816	$ 220,428	$ 158,000	$ -	$ 125,227	**$785,258**

Fiscal Year 2023								
Project H	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$ 187,540	$ 5,000	$ 44,816	$ 224,853	$ 158,000	$ -	$ 134,158	**$754,367**

6. References

Korman, J., and Campana, S.E., 2009, Effects of hydropeaking on nearshore habitat use and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society, v. 138, no. 1, p. 76-87, https://doi.org/10.1577/T08-026.1.

Korman, J., Yard, M.D., and Yackulic, C.B., 2016, Factors controlling the abundance of rainbow trout in the Colorado River in Grand Canyon in a reach utilized by endangered humpback chub: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 105-124, http://dx.doi.org/10.1139/cjfas-2015-0101.

Korman, J., Yard, M.D., and Kennedy, T.A., 2017a, Trends in rainbow trout recruitment, abundance, survival, and growth during a boom-and-bust cycle in a tailwater fishery: Transactions of the American Fisheries Society, v. 146, no. 5, p. 1043-1057, https://doi.org/10.1080/00028487.2017.1317663.

Korman, J., and Yard, M.D., 2017b, Effects of environmental covariates and density on the catchability of fish populations and interpretation of catch per unit effort trends: Fisheries Research, v. 189, p. 18-34, https://doi.org/10.1016/j.fishres.2017.01.005.

Rogers, S., 2015, Fisheries management plan, Colorado River-Lees Ferry 2015-2025: Phoenix, Arizona Game and Fish Department, Sport Fish Restoration, Region II Fish Program, 15 p.

Petty, T.R., Secretary's Designee, Assistant Secretary for Water and Science, 2019, Glen Canyon Dam Adaptive Management Program guidance—August 14, 2019 memorandum: Washington, D.C., U.S. Department of the Interior, Office of the Secretary, 4 p.

Runge, M.C., Yackulic, C.B., Bair, L.S., Kennedy, T.A., Valdez, R.A., Ellsworth, C., Kershner J.L., Rogers, R.S., Trammell, M.A., and Young, K.L., 2018, Brown trout in the Lees Ferry reach of the Colorado River—Evaluation of causal hypotheses and potential interventions: U.S. Geological Survey Open-File Report 2018–1069, 83 p., https://doi.org/10.3133/ofr20181069.

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

Yackulic, C.B., Korman, J., Yard, M.D., and Dzul, M.C., 2018, Inferring species interactions through joint mark-recapture analysis: Ecology, v. 99, no. 4, p. 812-821, https://doi.org/10.1002/ecy.2166.

Yackulic, C.B., 2020, Predictions, populations, and energetic constraints—presentation: Phoenix, Ariz., U.S. Geological Survey, Glen Canyon Dam Adaptive Management Program annual reporting meeting, January 13, 2020, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-PredictionsPopulationsEnergeticConstraints-Presentation-508-UCRO.pdf.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, J., 2011, Trout piscivory in the Colorado River, Grand Canyon—Effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society, v. 140, no. 2, p. 471-486, https://doi.org/10.1080/00028487.2011.572011.

Project I: Warm-water Native and Non-Native Fish Monitoring and Research

1. Investigators

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring Center
Dave Rogowski, Fish Biologist, Arizona Game and Fish Department

2. Project Summary and Purpose

Maintaining self-sustaining native fish populations within the Colorado River and minimizing the presence and expansion of aquatic invasive species are two specific resource goals outlined in the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) and associated Biological Opinion (BiOp) for the operation of Glen Canyon Dam (DOI, 2016a, b). These two resource goals are closely linked together in that introduced warm-water fish are largely incompatible with Colorado River native fish (Marsh and Pacey, 2005; Minckley and Marsh, 2009). Introduced warm-water sport fish prey upon juvenile native fish, and once established, can cause rapid disappearance of native fish (Moyle and others, 1986). In both the upper and lower Colorado River Basins, warm-water predatory fish are implicated in the lack of recruitment and subsequent population declines in native fish (Mueller, 2005; Martinez and others, 2014). Control methods are typically the most cost effective and successful when invasions are detected early (Leung and others, 2002; Dawson and Kolar, 2013). A robust monitoring program increases the likelihood that a new invasion will be detected early and that management actions can be taken to control pest species. Water levels in Lake Powell have decreased in recent years because of ongoing drought. This causes warm surface waters to be entrained into the penstocks and released downstream. While warmer water provides better thermal conditions for native Colorado River fish, it also increase the likelihood that warm-water introduced fish will become established and negatively impact populations of native fish.

This project proposes to continue long-term standardized monitoring throughout the Colorado River from Lees Ferry (River Mile [RM] 0) to Pearce Ferry (RM 281) for the combined purposes of tracking the status of native fish as well as identifying new invasive aquatic species. In the previous workplan we identified channel catfish and green sunfish as two invasive species that pose particularly high risks to Colorado River native fish. There are no catfish species native to the Colorado River, therefore native Colorado River fish did not evolve mechanisms to avoid catfish predation. Native fish are particularly vulnerable to predation by catfish predators, especially under turbid conditions (Ward and Vaage, 2019). Green sunfish were also identified as a particularly high-risk species because of their aggressive nature, high piscivory and known ability to rapidly colonize new environments and displace native fish. In this workplan we also propose to quantify the risks posed by these two species.

3. Proposed Work

Project Elements

Project Element I.1. System-wide Native Fish and Invasive Aquatic Species Monitoring

The objective of this project element is to provide long-term data on the longitudinal distribution and status of the fish community in the mainstem Colorado River from Lees Ferry (RM 0) to Pierce Ferry (RM 281). System-wide monitoring is necessary to assess populations of native fish and to monitor the status of nonnative fish to ensure that LTEMP goals are being met. Annually, Arizona Game and Fish Department (AZGFD) has been conducting two spring river trips from Lees Ferry to Diamond Creek, and one fall river trip from Diamond Creek to Pearce Ferry, and uses standardized electrofishing, hoop netting catch, and angling catch per unit effort (CPUE) indices to track the relative status and trends of most common native and nonnative fish species in the Colorado River ecosystem (CRe). The current work plan will continue this standardized monitoring (14 nights of sampling per trip) which has been occurring annually since 2000 (Makinster and others, 2010).

In addition to evaluating the risks posed by invasive fish species we will also continue to evaluate prevalence of fish parasites such as Asian fish tapeworm in humpback chub using non-lethal methods (Ward, 2007). Monitoring of fish parasites such as Asian fish tapeworm is identified as a requirement of the 2016 BiOp for the operation of Glen Canyon Dam. Monitoring for Asian fish tapeworm infestation in humpback chub will occur within the mainstem Colorado River and the Little Colorado River and will provide a baseline context with which to evaluate the potential impacts of this invasive parasite on endangered humpback chub populations.

Project Element I.2. Invasion and Colonization Dynamics of Warm-water Invasive Fish

This project element proposes to improve detection of warm-water invasive fish that are passing through Glen Canyon Dam. The goal of this monitoring effort is to improve detection ability and efficiency so that management agencies can better evaluate risks and deploy resources rapidly when needed to contain or eradicate aquatic invaders. The Glen Canyon slough at -12 mile provides a unique, low-cost opportunity to evaluate the number of invasive warm-water fish that are passing through Glen Canyon Dam. Warm-water fish are naturally attracted to the warm Glen Canyon slough. A small removable fiberglass fishway will be constructed and placed at the back of the Glen Canyon slough to trap and hold fish that move from the mainstem Colorado River into the warmer water of the upper slough. The trap on this fishway will be monitored during the summer months to quantify the number and size distribution of warm-water fish that are attempting to colonize the slough. In addition, the AZGFD will continue to conduct two extra nights of monitoring using electrofishing in the Lees Ferry Reach to increase potential detection of new invasive fish passing through the dam. Tributaries are another high-risk pathway for warm-water fish invasions. This project proposes to quantify the number of introduced fish that

are typically washed into the Colorado River each year during monsoon season from isolated pools within the Little Colorado River, Kanab Creek and Spencer Creek and to evaluate the potential threat that invasions from these tributaries pose for Colorado River native fish. In conjunction with this project water samples will be collected and environmental DNA (eDNA) techniques will be used to will be used to assess the presence and relative abundance of invasive fish in the mainstem Colorado River in areas upstream and downstream of these tributaries.

Project Element I.3. Impacts of Channel Catfish on Native Fish in the Little Colorado River

The objective of this project element is to quantify the potential impacts channel catfish may have on native fish populations in the Little Colorado River. Work conducted in the FY 2018-20 Triennial Work Plan indicates large channel catfish are in higher abundance than previously known and distributed widely throughout the entire area inhabited by humpback chub within the Little Colorado River. We will continue to catch and mark channel catfish in the Little Colorado River using angling techniques to obtain population and age estimates. Relative predation vulnerability of Colorado River native fish to channel catfish under varying temperature and turbidity conditions will be assessed in the laboratory in overnight trials using methods similar to those conducted for trout (Ward and others, 2016) and smallmouth bass (Tennant, 2018). Field evaluations of catfish diets will be used in conjunction with relative abundance data to predict population level impacts of these warm-water invasive fish on humpback chub within the Little Colorado River.

4. Budget

Fiscal Year 2021								
Project I	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$189,268	$3,000	$21,520	$106,857	$246,550	$0	$52,287	**$619,482**

Fiscal Year 2022								
Project I	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$216,431	$3,000	$16,100	$126,172	$273,110	$0	$95,002	**$729,815**

Fiscal Year 2023								
Project I	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$244,187	$3,000	$14,600	$112,858	$238,550	$0	$112,057	**$725,252**

5. References

Dawson, V.K., and Kolar, C.S., eds., 2003, Integrated management techniques to control nonnative fishes—completion report: La Crosse, Wisc., prepared for the Bureau of Reclamation by U.S. Geological Survey, Upper Midwest Environmental Sciences Center, 146 p. plus appendices, https://www.umesc.usgs.gov/documents/reports/2003/bor_final_report.pdf.

Leung, B., Lodge, D.M., Finnoff, D., Shogren, J.F., Lewis, M.A., and Lamberti, G., 2002, An ounce of prevention or a pound of cure—Bioeconomic risk analysis of invasive species: Proceedings of the Royal Society B—Biological Sciences, v. 269, no. 1508, p. 2407-2413, https://doi.org/10.1098/rspb.2002.2179.

Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona—2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010-1246, 26 p., https://pubs.usgs.gov/of/2010/1246/.

Marsh, P.C., and Pacey, C.A., 2005, Immiscibility of native and non-native fishes, in Brouder, M.J., Springer, C.L., and Leon, C.S., eds., Restoring natural function within a modified riverine environment—The lower Colorado River, Albuquerque, N.Mex., July 8-9, 1998 and in Restoring native fish to the lower Colorado River—Interactions of native and non-native fishes, Las Vegas, Nev., July 13-14, 1999, Proceedings of two symposia: p. 59-63.

Martinez, P., Wilson, K., Cavalli, P., Crockett, H., Speas, D.W., Trammell, M., Albrecht, B., and Ryden, D., 2014, Upper Colorado River Basin nonnative and invasive aquatic species prevention and control strategy—final report: Lakewood, Colo., U.S. Fish and Wildlife Service Upper Colorado River Endangered Fish Recovery Program, 125 p., http://www.coloradoriverrecovery.org/general-information/program-elements/nna/BASINWIDENNFSTRATEGYFeb2014.pdf.

Minckley, W.L., and Marsh, P.C., 2009, Inland fishes of the greater southwest—Chronicle of a vanishing biota: Tucson, University of Arizona Press, 426 p.

Moyle, P.B., Li, H.W., and Barton, B.A., 1986, The Frankenstein effect—Impact of introduced fishes on native fishes in North America, in Stroud, R.H., ed., Fish culture in fisheries management: Bethesda, Md., American Fisheries Society, p. 415-426.

Mueller, G.A., 2005, Predatory fish removal and native fish recovery in the Colorado River mainstem—What have we learned?: Fisheries, v. 30, no. 9, p. 10-19, https://doi.org/10.1577/1548-8446(2005)30[10:PFRANF]2.0.CO;2.

Tennant, L.A., 2018, Effects of body size on vulnerability to predation of young-of-year roundtail chub (*Gila robusta*) stocked into the Verde River, Arizona: Flagstaff, Northern Arizona University, M.S. thesis.

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

U.S. Department of the Interior, 2016, U.S. Fish and Wildlife Service Biological Opinion (BiOp)—Appendix E, in Record of Decision (ROD) for the Glen Canyon Dam Long-term Experimental Plan final Environmental Impact Statement (LTEMP FEIS): Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, p. E-1—E-94, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Ward, D.L., 2007, Removal and quantification of Asian tapeworm from bonytail chub using Praziquantel: North American Journal of Aquaculture, v. 69, no. 3, p. 207-210, https://doi.org/10.1577/A06-054.1.

Ward, D.L., Morton-Starner, R., and Vaage, B., 2016, Effects of turbidity on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout: Journal of Fish and Wildlife Management, v. 7, no. 1, p. 205-212, https://doi.org/10.3996/102015-JFWM-101.

Ward, D.L., and Vaage, B.M., 2019, What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?: Journal of Fish and Wildlife Management, v. 10, no. 1, p. 196-205, https://doi.org/10.3996/042018-JFWM-031.

Project J: Socioeconomic Research

1. Investigators

Lucas Bair, Economist, U.S. Geological Survey
Josh Abbott, Professor, Arizona State University, School of Sustainability
Paul Grams, Research Hydrologist, U.S. Geological Survey
Eric Mueller, Professor, Southern Utah University, Physical Science
Chris Neher, Economist, Montana State University, Department of Mathematical Sciences
Michael Springborn, Professor, UC Davis, Environmental Science and Policy
Charles Yackulic, Research Statistician, U.S. Geological Survey

2. Project Summary and Purpose

Project J contains research elements that collect and integrate socioeconomic information with data and predictive models from ongoing long-term physical and biological monitoring and research led by the Grand Canyon Monitoring and Research Center (GCMRC). The project elements improve the ability of the Glen Canyon Dam Adaptive Management Program (GCDAMP) resource managers and stakeholders to evaluate management actions and prioritize monitoring and research. This project involves three interrelated socioeconomic research elements that address novel resource management challenges and build on research in the FY 2018-20 Triennial Work Plan (TWP):

a) The development and integration of predictive biological and physical models with economic metrics to evaluate and prioritize monitoring of, and research on, resources downstream of Glen Canyon Dam (GCD), including the anticipated success (or lack thereof) of proposed flow experiments in the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) (Element 1);

b) The design, implementation, and monitoring of the impacts of an incentivized harvest program to reduce brown trout abundance in Lees Ferry (Element 2); and

c) The survey of recreational angler and whitewater boater's preferences for flow characteristics, in accordance with GCD maintenance and LTEMP EIS experimental flows (Element 3).

The proposed project elements address the LTEMP Record of Decision (ROD) (U.S. Department of Interior 2016a) resource goals related to humpback chub, sediment, invasive fish, and hydropower, as specified in each project element.

3. Proposed Work

Project Elements

Project Element J.1. Predictive Models for Adaptive Management

This project element includes the development of predictive models to improve the GCDAMP's capacity to evaluate and prioritize monitoring, research and management alternatives specific to the operation of GCD, including proposed flow experiments in the LTEMP EIS (U.S. Department of Interior 2016a). This project will further refine bioeconomic modeling methods to evaluate rainbow trout management strategies in relation to humpback chub population goals (Bair and others, 2018; Donovan and others, 2019; ongoing research in FY 2018-20 TWP Project J.2). Predictive modeling of sediment deposition and hydropower generation, across various flow and sediment input scenarios, will also be undertaken based on recent development of predictive sandbar modeling capabilities (Mueller and others, 2018; Mueller and Grams, 2019).

Humpback Chub

Bioeconomic modeling has led to robust estimates of management triggers for rainbow trout control strategies based on humpback chub recovery goals (Bair and others, 2018; Donovan and others, 2019). This research has also provided insight into the importance of parametric uncertainty related to rainbow trout and humpback chub population dynamics. In the FY 2018-20 TWP, we continue to develop the bioeconomic modeling capacity to estimate the effectiveness and efficiency of trout management flows (TMFs) and the impact of nonstationary elements (e.g., hydrology) to humpback chub recruitment in the Little Colorado River. Important questions remain about the precision of abundance estimates of invasive fish needed to improve the effectiveness and efficiency of management interventions to meet humpback chub recovery goals. This project sub-element will advance the ongoing bioeconomic modeling (Bair and others, 2018; Donovan and others, 2019; FY 2018-20 TWP Project J.2) needed to inform on rainbow trout and humpback chub population dynamics. Specifically, we will assess the importance of precision of estimates of adult humpback chub and rainbow trout recruitment and abundance in Lees Ferry and Marble Canyon, respectively. This project sub-element will improve the GCDAMP's capacity to evaluate and prioritize rainbow trout and humpback chub monitoring and research and facilitate achieving the LTEMP ROD humpback chub resource goal to, 'meet humpback chub recovery goals.'

Sandbars

The LTEMP ROD sediment resource goal for sediment is to, 'increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.' One of the challenges faced in implementation of the LTEMP ROD sediment resource goal is a lack of information needed to predict sandbar response to High-Flow Experiments (HFEs) or other experimental flows of different magnitude, duration, or hydrograph shape. While annual surveys

and remote cameras provide an assessment of changes in sandbar size, linking physical or numerical models to observed sandbar response is necessary to provide a framework for evaluating the effects of different sediment concentration and flow scenarios, over time. In the FY 2015-17 TWP, progress was made on identifying groupings (classes) of sandbars based on geomorphic settings that respond similarly to HFEs and other dam releases, and on developing a simple site-based numerical model (hereafter, sandbar model) for predicting sandbar volume changes based on site geometry, streamflow and sand concentration data (Mueller and others, 2018; Mueller and Grams, 2019).

The primary objective of this project sub-element is to use the physically-based sandbar model of individual bar response, using flow, stage, sediment concentration, and sediment grain size, to predict changes in sandbar size, while considering the economic costs to hydropower, over various future flow and sediment scenarios. This research will allow us to 'explore the feasibility of [HFEs while] ...modeling for improvements and efficiencies that benefit [program] resources,' such as hydropower (Petty, 2019). In addition, simulation of the sandbar model on an annual timestep will allow us to explore the applicability of the sandbar model to hydrograph design options in terms of peak flow (below, at, or above power plant capacity), hydrograph asymmetry (up- and down-ramp rates), and duration, in order to evaluate how these variables, while considering economic costs, affect sandbar deposition and erosion. This project sub-element will allow for opportunities to 'increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes' while considering economic costs to hydropower over a multiple year time horizon (U.S. Department of Interior, 2016a). For example, this project sub-element will provide the capability to assess what combination of conditions would maximize sediment volume and minimize economic costs associated with HFEs and other experimental and maintenance flows over a multiple year time horizon.

Project Element J.2. Brown Trout Incentivized Harvest

The National Park Service Glen Canyon National Recreation Area (GCNRA) is proposing a brown trout incentivized harvest program. The objective of the program is to control brown trout abundance through angler removal, consistent with the LTEMP ROD resource goal to, 'minimize or reduce the presence and expansion of aquatic nonnative invasive species.' In Project J.2 we will assist GCNRA in the design (i.e., payment structure) and analysis of data collected for the program.

The primary objective of this project element is to evaluate how structure of the monetary payout from the program influences participation, harvest, and retention rates within the brown trout fishery. This information will inform GCNRA on cost-effective approaches to meet removal objectives for brown trout abundance at Lees Ferry. We will achieve our research objectives through collaboration between the GCNRA, GCMRC (biologists involved in Project H), and

Arizona State University. We will also work alongside the Glen Canyon Conservancy, the organization that will coordinate the collection of brown trout and angler payment for the pilot program. Supplemental data will be obtained from Lees Ferry creel and collaboration with Arizona Game and Fish Department. The project will provide information on the scope of participation in the program, the geographic and demographic characteristics of participants, catch rates of anglers for both brown trout and other species (e.g., rainbow trout) as a result of the program, and the temporal variability of angler's catch rates as the abundance and vulnerability of the brown trout population changes.

In addition to program design and analysis, Project J.2 will undertake a survey of anglers following implementation of the program. The angler survey, utilizing methods to survey anglers in the FY 2015-17 TWP, will obtain information on angler attitudes and preferences for the program, including those who participated in the program but did not catch and retain a brown trout and those who did not participate in the program. As was the case with the recent angler surveys (Duffield and others, 2016), the proposed project will use a mail survey contact method with a follow-up protocol for non-responders. Angler contact information will be collected as part of the Lees Ferry creel in collaboration with Arizona Game and Fish Department. The angler survey is critical in our attempts to garner a complete understanding of angler behavior and participation in the program.

Project Element J.3. Recreation Monitoring and Research

The Grand Canyon Protection Act (GCPA) of 1992 states that, "long-term monitoring of Glen Canyon Dam shall include any necessary research and studies to determine the effect of the Secretary's actions under section 1804(c) on the…recreational…resources of Grand Canyon National Park and Glen Canyon National Recreation Area" (GCPA, sec. 1805(b)). Recent research has established important seasonal and flow attributes to recreational users in Glen and Grand Canyons (Bair and others, 2016; Duffield and others, 2016; Neher and others, 2017; and Neher and others, 2019). This work has also demonstrated the temporal stability of recreational preferences for flow attributes over several decades of dam operations (Bishop and others, 1987; Neher and others, 2017).

While we understand the relationship between dam operations and recreational preferences and economic values related to angling in GCNRA and whitewater boating in Grand Canyon National Park (GCNP), uncertainties regarding specific preferences associated with daily flow stage and fluctuation still remain. For example, Neher and others (2018) found no statistically significant difference between whitewater boater's preferences for daily fluctuations of 8,000 ft^3/s and constant flows. However, Bishop and others (1987) found that there is a strong relationship between whitewater boater economic values for large fluctuations (10,000 – 31,500 ft^3/s) at moderate flows levels (22,000 ft^3/s). Also, the angling experience in Glen Canyon has changed since studies conducted in 2016 (Bair and others, 2016; Duffield and others, 2016), as a

result of experimental flows (Rogowski and others, 2019). These changes in the angler experience in combination with the uncertainty in whitewater boaters' preferences for narrower ranges of fluctuations, warrant further study of recreational preferences for flow stage and fluctuation.

The objective of this project element is to further refine our understanding of recreational preferences for flow attributes. To accomplish the project element objective, recreational surveys will be conducted in accordance with maintenance and experimental (e.g., TMFs, extended duration HFEs) flows to better understand recreationists' preferences and economic values associated with flows. Specifically, surveys of anglers in GCNRA and whitewater boaters in GCNP will be conducted in accordance with maintenance and experimental flows. Prior to implementation of individual surveys, the Socioeconomic Ad Hoc Group will convene to review questions proposed by principal and co-principal investigators. This proposed project will use a combination of in-person and mail survey methods. The participants will be intercepted during or immediately following a maintenance or experimental flow event. The limited temporal nature of a flow event requires that we attempt to intercept the entire population of recreational anglers and whitewater boaters that experience the flow event. 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 FY 2015–17 TWP, Project Element 13.3).

4. Budget

Fiscal Year 2021								
Project J	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$106,790	$4,000	$1,500	$0	$57,000	$0	$17,430	**$186,720**

Fiscal Year 2022								
Project J	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$126,493	$4,000	$1,500	$0	$57,000	$0	$33,388	**$222,381**

Fiscal Year 2023								
Project J	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$141,617	$4,000	$1,500	$0	$38,500	$0	$42,347	**$227,964**

For Project Element J.3, minor supplemental funding from the Experimental Fund would cover additional salary, logistics, and travel for recreational surveys in order to conduct monitoring and research during maintenance and LTEMP flow experiments (e.g., TMFs, extended-duration HFEs). The costs for this experimental work are estimated to be no more than $8,000 to $10,000 per maintenance or LTEMP experiment event.

5. References

Bair, L.S., Rogowski, D.L., and Neher, C., 2016, Economic value of angling on the Colorado River at Lees Ferry—Using secondary data to estimate the influence of seasonality: North American Journal of Fisheries Management, v. 36, no. 6, p. 1229-1239, https://doi.org/10.1080/02755947.2016.1204388.

Bair, L.S., Yackulic, C.B., Springborn, M.R., Reimer, M.N., Bond, C.A., and Coggins, L.G., 2018, Identifying cost-effective invasive species control to enhance endangered species populations in the Grand Canyon, USA: Biological Conservation, v. 220, p. 12-20, https://doi.org/10.1016/j.biocon.2018.01.032.

Bishop, R.C., Boyle, K.J., Welsh, M.P., Baumgartner, R.M., and Rathbun, P.R., 1987, Glen Canyon Dam releases and downstream recreation—An analysis of user preferences and economic values: Madison, Wisc., Huberlein-Baumgartner Research Service, submitted to Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies report no. GCES/27/87, 188 p.

Donovan, P., Bair, L.S., Yackulic, C.B., and Springborn, M.R., 2019, Safety in numbers—Cost-effective endangered species management for viable populations: Land Economics, v. 95, no. 3, p. 435-453, https://doi.org/10.3368/le.95.3.435.

Duffield, J., Neher, C., and Patterson, D., 2016, Economic analysis of Glen Canyon angler and Grand Canyon whitewater visitor surveys: Missoula, University of Montana, Department of Mathematical Sciences, prepared for U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 160 p.

Mueller, E.R., P.E. Grams, J.E. Hazel Jr., J.C. Schmidt, 2018, Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon: Sedimentary Geology, v. 363, p. 181–199, https://doi.org/10.1016/j.sedgeo.2017.11.007.

Mueller, E.R., and Grams, P.E., 2018, Modeling decadal changes in sandbar volume using sub-daily records of flow and sand concentration downstream from a large dam—conference paper, Joint 70th Rocky Mountain Annual Section/114th Cordilleran Annual Section Meeting: Flagstaff, Ariz., Geological Society of America, https://doi.org/10.1130/abs/2018RM-314039.

Neher, C., Bair, L.S., Duffield, J., Patterson, D., and Neher, K., 2018, Convergent validity between willingness to pay elicitation methods—An application to Grand Canyon whitewater boaters: Journal of Environmental Planning and Management, v. 62, no. 4, p. 611-625, https://doi.org/10.1080/09640568.2018.1435411.

Neher, C.J., J. Duffield, L.S. Bair, D. Patterson, K. Neher, 2017, Testing the limits of temporal stability: willingness to pay values among Grand Canyon whitewater boaters across decades: Water Resources Research, v. 53, https://doi.org/10.1002/2017WR020729.

Petty, T.R., Secretary's Designee, Assistant Secretary for Water and Science, 2019, Glen Canyon Dam Adaptive Management Program guidance—August 14, 2019 memorandum: Washington, D.C., U.S. Department of the Interior, Office of the Secretary, 4 p.

Rogowski, D.L., 2019, Lees Ferry trout monitoring—presentation: Tempe, Ariz., Glen Canyon Dam Adaptive Management Program Annual Reporting meeting, January 2020.

U.S. Department of Interior, 2016a, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

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

Project K: Geospatial Science, Data Management and Technology Project

1. Investigators

Thomas M. Gushue, IT Specialist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
James Hensleigh, IT Specialist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
TBD, Geographer, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

A crucial component of any long-term adaptive management program is the proper management and accessibility of its data resources necessary for measuring the status, trends, and experimental results related to the program's objectives. The data collected through the U.S. Geological Survey's GCMRC are a vital resource used to determine the status of the natural resources identified through the Glen Canyon Dam Adaptive Management Program (GCDAMP) and to make timely decisions on dam operations. The primary purpose of this project is to provide high-level support to GCDAMP-funded science efforts in the disciplines of geospatial science, data management, database administration, and emerging information technologies.

Shifts in the geospatial and information technology industries are pushing the boundaries on how data can be managed and made accessible to outside entities. Much of this change is driven by advances in technology—from improved sensors for monitoring the earth, to increased digital data storage capacity, to newer computer systems designed for processing large data sets more efficiently, to the greater emphasis of the "Internet of Things" where the reliance of web-based technologies have revolutionized our world.

A common thread for the different aspects of this project is to continue to advance GCMRC's ability to leverage many of these new technologies for the benefit of the GCMRC, the science projects described within this work plan, and the larger GCDAMP. Work performed within this project makes it possible to share important information about trends in resources of the Colorado River ecosystem to the GCDAMP through web-based, interactive tools and mapping products, allowing the GCDAMP to make better informed, time-sensitive decisions on experimental and management actions under the 2016 Long-Term Experimental and Management Plan (LTEMP) and the associated Record of Decision (ROD) (U.S. Department of Interior, 2016).

3. Proposed Work

Project Elements

Project Element K.1. Enterprise GIS, Geospatial Analysis and Processing

Work performed within this element will continue to provide the same Geographic Information System (GIS) services that have been consistently provided to the GCMRC for previous work plans. This project is continually striving to improve upon GCMRC's ability to manage its expanding data resources. For several years the main focus was on designing, developing and maintaining consistent and accurate geospatial data sets, workflows and analyses in support of science projects. In the FY 2021-23 Triennial Work Plan (TWP), this project will continue to support research and monitoring projects by providing geospatial expertise to most projects on field mapping methods, development of customized maps, sample site unit definition and selection, GIS layer development and metadata review, and GIS tool development and support. GIS staff support also involves the oversight and supervision of science project staff with GIS-related tasks including, spatial analysis in support of projects, training for staff and cooperators in GIS data entry and database management concepts, data processing techniques, production of printed maps and online map products, error troubleshooting, and other basic GIS methods and techniques.

Key aspects of the work performed in this element include the processing and analysis of large, complex geospatial data sets that often benefit multiple projects. An example of this from the FY 2018-20 Triennial Work Plan (TWP) is processing and analysis work on the Glen Canyon channel map data set. Specific tasks performed by GIS staff included processing derived data sets from the 2013 Digital Surface Model (DSM) to remove vegetation from the surface, thus creating a bare-ground elevation surface to be used in conjunction with field-based topography and bathymetry elevation data to make a composite channel map.

This project maintains an enterprise GIS platform that is built upon Environmental Systems Research Institute (ESRI) ArcGIS Portal and Server applications and is used for maintaining existing online data resources. Data services developed through this online system can then be shared through multiple endpoints including cloud-based content delivery systems, custom web applications hosted on-premises, and through other novel applications. During the FY 2021-23 TWP cycle, we will continue to expand on content that is available through this system, and work to improve the functionality that is available as well as develop new, web-based analytical tools. Additional GIS Administration tasks related to science support include the testing and migration of computer systems to newer versions of the most commonly used GIS/Remote Sensing software, maintaining licensing information, and/or working with Information Technology (IT) staff to ensure all licenses, software, extensions, add-ons, and custom applications work properly.

Project Element K.2. Data Management and Database Administration

During the last three years this project has worked towards addressing the need to expand concepts developed in GIS to other data resources across GCMRC. This project will now incorporate much of the relational database work in support of other science projects defined in this work plan. By building the expertise and capacity in data management, data acquisition, and relational database administration within one group, this project will now be better aligned to provide more comprehensive support to resource-specific science efforts and to the larger GCDAMP community.

Data management in support of research and monitoring has been a part of GCMRC since its inception and was specifically outlined in the 1995 EIS that clearly defines the Center's responsibilities for managing data in support of the GCDAMP (U.S. Department of the Interior, 1995). The concept of data management encompasses many facets including, but not limited to, data preservation, design, development, maintenance of systems and applications designed to store and serve the data, building systems that provide access to these data, and performing the necessary documentation of data sets. This work was also supported in the 1995 ROD – specifically in GCDAMP Goal 12, to maintain a high-quality monitoring, research and adaptive management program – and in subsequent documents including the most recent LTEMP EIS. Success of the LTEMP will rely heavily on the GCMRC's ability to continue to improve on data accessibility for stakeholders, managers, and, when appropriate, the general public.

Database Administration

Work proposed within this project element include the continued maintenance of existing relational databases in support of LTEMP related science efforts, and in some cases, the design and development of new databases for projects or resources. Existing, resource-specific databases that have been developed and managed through this project include: Sandbar Area and Volume, Riparian Vegetation Survey, Geodetic Network Control, and Lake Powell Water Quality. For the FY 2021-23 TWP, the primary focus will be on the full documentation, redesign and re-implementation of the existing fish monitoring database. The fish monitoring database is one of the most important data resources maintained by GCMRC, and this project is now better positioned to greatly improve the entire workflow process for storing, reviewing, analyzing and accessing fish aquatic information. The migration of all project data to relational databases has begun and will continue throughout this next TWP. The shift in how we approach our data resources will provide a consistent and stable platform for conducting much of the monitoring and research activities within this work plan and beyond.

Cloud-based Data Management

Since 2017, this project has led GCMRC's efforts to adopt and use cloud-based environments for providing better access to its data and applications. By working with the USGS Cloud Hosting Solutions (CHS) team, the GIS project has continued to lead the way for GCMRC in expanding the use of the Amazon Web Services (AWS) cloud environment for leveraging cost effective, advanced cloud computing solutions, application development and deployment, and providing access to information through some of the most advanced data serving systems available today.

Modern application of enterprise databases involves standardized source control of all application components, advance system configuration of both local desktop and server environments, and the proper deployment and management of AWS cloud-based components. There are many benefits to leveraging these cloud environments for science applications. They offer scalable resources, many of which only incur costs while the components are being accessed. The cost of server maintenance, security, data/application availability, storage, and redundancy are all managed by AWS, thus reducing the amount of time needed internally for information technology staff to perform these duties. It is proposed this project will continue to lead GCMRC in adoption of a hybrid-cloud strategy for future data management and application development.

Project Element K.3. Remote Monitoring and Advanced Technology Support

Many of the technologies that GCMRC's science relies on have advanced over the past two decades. This trend is expected to continue and likely accelerate in the coming years. Efforts within this project strive to stay engaged in relevant technological advancements, and in some cases, be on the leading edge of these changes.

In FY 2017, GCMRC's Geospatial Science and Technology Project became involved with an Internet of Things (IoT) Sensor pilot project to test the feasibility of connecting sensors deployed in the field to the AWS – Cloud Hosting Solutions cloud environment. This pilot work required the reconfiguration of an existing field sensor system (Vaisala weather station) already deployed at Lees Ferry and development of two-way communication capabilities with the sensor and data logger via cellular transmission to the Amazon cloud. The main objective was to demonstrate the ability to automate the transmission of data from the field to the cloud at some predefined interval, and to allow users to subscribe to "alerts" based on defined data values that would then perform some other action—in this case send a text message regarding extreme air temperature alerts. We successfully achieved this initial goal in 2018 and presented our work at the inaugural USGS Sensor Summit workshop in Denver. Our IoT efforts have now expanded to include the transmission of water quality data from an instrument located at the Lees Ferry Gage Station, River Mile 0 as of January 2020.

The objective for continuing this work into FY 2021-23 is to develop a connected network of sensors through Glen Canyon reach from Glen Canyon Dam downstream to Lees Ferry, Arizona. Given the proximity to other potential IoT sensor deployment sites (Wahweap Bay on Lake Powell, Paria River gage, and water quality instruments located at the long-term sediment monitoring stations in Marble and Grand Canyons), it is possible that during this next three-year effort we could have a canyon-wide, near real-time monitoring network for water quality of the Colorado River. This would not only be the first system of its kind, but also will greatly increase the flow of water quality information to GCDAMP stakeholders on the status of this vital resource.

This project element also tracks the technical support and electrical engineering expertise provided to other research projects described in this work plan. The type of work performed in this element is varied and must at times adjust to respond to emerging needs within projects or critical responses to system failures. Listed below are specific tasks with individual projects identified, where possible. Some work performed in this element inherently benefits the Center as a whole by improving upon the design and development of common components used by most remote monitoring systems deployed by GCMRC.

4. Budget

Fiscal Year 2021								
Project K	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$465,245	$4,607	$6,100				$66,633	**$542,585**

Fiscal Year 2022								
Project K	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$425,910	$4,940	$6,100				$104,868	**$541,818**

Fiscal Year 2023								
Project K	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$438,687	$3,274	$6,100				$125,457	**$573,518**

5. References

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

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Project L: Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP

1. Investigators

Joel B. Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Laura Durning, Research Specialist Sr., Northern Arizona University

2. Project Summary and Purpose

This project seeks to acquire high-resolution multispectral imagery and a digital surface model (DSM) of the Colorado River and riparian area from the forebay of Glen Canyon Dam (GCD) downstream to Lake Mead, and along the major tributaries to the Colorado River. The proposed schedule for this data collection mission is in May 2021, during the first year of the FY 2021-23 Triennial Work Plan (TWP). The data sets derived from remote sensing overflights (Table 1) have proven to be extremely valuable to most of the research projects conducted by GCMRC over the past two decades. Importantly, scientific research which relied heavily on these data were the basis for the 2016 Long-Term Experimental and Management (LTEMP) planning, and data derived from the 2021 overflights will be used in the LTEMP Record of Decision (ROD) implementation process (U.S. Department of Interior, 2016). GCMRC's Scientific Monitoring Plan in support of LTEMP, notes that the ROD "calls for a comprehensive, decadal-scale assessment of the impact of dam operations on sandbar resources and on the status of humpback chub" (VanderKooi and others, 2017).

Given that the most recent overflight was previously conducted in 2013, and given the physical, geographic and logistical constraints of the Colorado River in Grand Canyon, remotely-sensed data are necessary to complement ground-based data collection and assist with the Center's efforts to effectively assess these impacts for the entire river ecosystem over decadal time frames. The imagery and derivative data products from overflight remote sensing are used either directly or indirectly by every science project proposed in this TWP to address every resource goal of the LTEMP. While this proposed work is discussed within the context of the FY 2021-23 TWP, the nature and justifications for conducting the overflight are directed at the GCMRC's ability to respond to and deliver information for the LTEMP implementation process that tracks decadal-scale changes to resources system-wide. As such, the overflight is a scientific effort that has both an immediate and a longer-term payoff; future LTEMP studies will require similar

information that can be effectively derived from remotely-sensed data acquired over coming decades. For these reasons, this project is mission critical to successfully inform the Glen Canyon Dam Adaptive Management Program on performance of the LTEMP ROD.

3. Proposed Work

Project Elements

Project Element L.1. Overflight Remote Sensing

[PI: Sankey; Co-I: Gushue, Kohl, Durning; Duration FY 2021-23]

GCMRC will implement a remote sensing overflight to collect digital, multispectral imagery and topography of the Colorado River ecosystem between GCD and Lake Mead in May 2021. To maintain consistency with previously collected digital, orthorectified aerial imagery (2002, 2009, 2013), the mission will be conducted during the same time of year (beginning on Memorial Day weekend and lasting for potentially one week or longer) and adhere to much of the same data collection parameters and significant logistical requirements as used in preceding missions. For data collection parameters, we require at least the same 4-band wavelength ranges (red, green, blue, and near infra-red), and the same or higher spatial resolution (20-cm pixel resolution), using the same or similar equipment (Leica ADS-80 camera mounted in fixed-wing aircraft), with the option of two cameras and aircraft being made available to increase the rate of data collection and reduce the impact on dam operations. Wavelengths and other technical details will be specified with the Scope of Work contract and will be similar to or improved upon those used in previous overflight missions. Specifications for the data acquisition necessitate that releases of the dam be held at a steady discharge of 8,000 ft^3/s for the duration of the overflight mission.

As such, the proposed 2021 overflight would be within the LTEMP flow regime, and we would request from and work with the Bureau of Reclamation and Western Area Power Administration to maintain the steady 8,000 ft^3/s discharge for the duration of the data collection period. This flow adjustment is required to maintain consistency with imagery data sets collected in previous years. This will allow for highly accurate image matching and change detection analysis. If a spring High-Flow Experiment (HFE) occurs in 2021, we will work closely with other GCMRC scientists and the Bureau of Reclamation to ensure all needs are met. We don't expect that the occurrence, or lack of occurrence, of an HFE in fall 2020 or spring 2021 will affect the proposed May mission. In fact, the LTEMP states that 'triggers for a fall HFE would be met 77% of the years in the LTEMP period', and thus HFE effects are simply an important aspect of the river system that are observed via periodic remote sensing overflights.

Table 1. Summary of primary datasets and examples of derived products from overflight missions used by GCDAMP science projects to achieve LTEMP resource goals.

Primary datasets produced from overflight missions	
Multispectral Imagery	Digital Topography
Products derived from primary datasets	
Website content and online maps	Cartographic products - River map books - Publication maps
Fish sampling unit system for mainstem Colorado River	Humpback chub monitoring system for Little Colorado River
Colorado River centerline and river mile system	Flowlines - Extracted from low-flow water's edge (~8,000 ft^3/s) in overflight imagery - Modelled from overflight topography and water surface elevation data
Land cover and landform mapping and change detection - Water, sand, vegetation land cover - Geomorphic basemap	Vegetation species classification
Campsite delineation - Campsite atlas	Topography data - Topographic change detection - Hydrologic flow modeling.

4. Budget

Fiscal Year 2021

Project L	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$186,800	$3,000	$561,000	$57,900	$80,600	$0	$115,600	**$1,005,000**

Fiscal Year 2022

Project L	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$195,200	$3,000	$6,000	$0	$83,000	$0	$51,500	**$338,800**

Fiscal Year 2023

Project L	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$214,700	$3,000	$6,000	$0	$85,500	$0	$65,200	**$374,400**

5. References

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

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

Project M: Administration

The Administration budget covers salaries for an administrative assistant, librarian, budget analyst, three members of the logistics support staff, as well as leadership and management personnel for the Grand Canyon Monitoring and Research Center (GCMRC). Leadership and management personnel salaries include those for the GCMRC Chief and Deputy Chief as well as half the salary for one program manager and a data specialist. Most of the travel and training costs for administrative personnel are included in this project as well as the cost of GCMRC staff to travel to Adaptive Management Working Group and Technical Working Group meetings. Operating expenses include: 1) General Services Administration vehicle costs including monthly lease fees, mileage costs, and any costs for accidents and damage; 2) Department of Interior vehicle costs including gas, maintenance, and replacements costs; 3) GCMRC's Information Technology equipment costs; and 4) a $20,000 annual contribution to the equipment and vehicles working capital fund. Cooperator funding is for support of the Partners in Science Program with Grand Canyon Youth.

Budget

Fiscal Year 2021									
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	Cooperators USGS	USGS Burden	Total
								14.00%	
M	*Administration*								
M.1	Admin	$758,244	$40,000	$138,000				$131,074	$1,067,318
M.2	Logistics	$266,808	$7,000			$11,000		$38,663	$323,471
M.3	IT			$100,000				$14,000	$114,000
	Total M	**$1,025,052**	**$47,000**	**$238,000**	**$0**	**$11,000**	**$0**	**$183,737**	**$1,504,789**

Fiscal Year 2022									
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	Cooperators USGS	USGS Burden	Total
								24.00%	
M	*Administration*								
M.1	Admin	$780,991	$40,000	$138,000				$230,158	$1,189,149
M.2	Logistics	$274,813	$7,000			$11,000		$67,965	$360,778
M.3	IT			$100,000				$24,000	$124,000
	Total M	**$1,055,804**	**$47,000**	**$238,000**	**$0**	**$11,000**	**$0**	**$322,123**	**$1,673,927**

Fiscal Year 2023									
Project	Project Description	Salary & Benefits	Travel & Training	Operating Expenses	Logistics	Cooperators (non-USGS)	Cooperators USGS	USGS Burden	Total
								28.00%	
M	*Administration*								
M.1	Admin	$801,240	$40,000	$138,000				$274,187	$1,253,427
M.2	Logistics	$281,973	$7,000			$11,000		$81,242	$381,215
M.3	IT			$100,000				$28,000	$128,000
	Total M	**$1,083,213**	**$47,000**	**$238,000**	**$0**	**$11,000**	**$0**	**$383,430**	**$1,762,642**

Project N: The Economic Impact of Electrical Production at Glen Canyon Dam: Hydropower's Role in Facilitating Renewable Energy Integration and Mitigating Emissions

1. Investigators

Lucas S. Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Dominique Bain, Researcher, Department of Energy, National Renewable Energy Laboratory
Clayton Palmer, Economist, Department of Energy, Western Area Power
Thomas Veselka, Engineer, Department of Energy, Argonne National Laboratory

2. Project Summary and Purpose

Holly Doremus (2011) argues that, 'adaptive management should be used only when it promises to improve management outcomes sufficiently to justify the additional costs it imposes.' When considering the cost of flow experiments, which alter the quantity and timing of hydropower generation, there are explicit costs associated with generation and implicit costs associated with changes in emissions. Therefore, to evaluate the costs imposed by adaptive management experiments, the total economic costs associated with alterations in hydropower generation and emissions should be understood. For example, total economic costs related to reoperation of Glen Canyon Dam (GCD), in various future energy sector scenarios, can be significantly decreased or increased by changes in emissions (Project N in the FY 2018-20 Triennial Work Plan (TWP); Bair, 2020).

Modeling these costs and the possible implications for future GCD operations and experimental flows is imperative for informed adaptive management and is aligned with the guidance in the Long-Term Experimental and Management Plan (LTEMP) Record of Decision (ROD) (2016) hydropower and energy resource goal[1] to 'minimize emissions and costs to the greatest extent practicable' and the memorandum from the Secretary's Designee[2], dated August 14, 2019, to prioritize the 'responsible development and production of renewable energy on federal lands.'

[1] The hydropower resource goal in the Record of Decision for the Long-Term Experimental and Management Plan Final Environmental Impact Statement is to, 'maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources.'
[2] The memorandum from the Secretary's Designee, dated August 14, 2019, providing Glen Canyon Dam Adaptive Management Program (GCDAMP) guidance states that the, 'Department of the Interior has recently prioritized the responsible development and production of renewable energy on federal lands. To this end, I encourage the GCDAMP to work within the LTEMP framework to seek ways to improve the value of the hydropower resource.

This research project addresses the LTMEP ROD hydropower and energy resource goal and the guidance of the Secretary's Designee by modeling the change in total economic value of hydropower production at GCD with altered operations in response to facilitating future renewable energy (e.g., wind, solar) integration and mitigating emissions in the Western Interconnection. If substantial economic benefits from renewable energy integration, bolstered by the mitigation of emissions become apparent, federal hydropower could be repurposed to address this opportunity. Repurposing hydropower generation at GCD could have drastic implications for daily and seasonal flows, which would be dependent on the type and location of additional renewable generation resources being integrated. Understanding the implications of renewable energy integration, electricity sector governance, and the mitigation of emissions is critical for adaptively managing the GCD and downstream resources while minimizing the total economic costs to the greatest extent practicable.

3. Proposed Work

Project Elements

Project Element N.1. The Economic Impact of Electrical Production at Glen Canyon Dam: Hydropower's Role in Facilitating Renewable Energy Integration and Mitigating Emissions

Hydropower generation at GCD is integrated into the Western Interconnect (i.e., electrical grid in the Western U.S.). In addition to GCD, electricity generation resources include other Colorado River Storage Project (CRSP) hydropower plants, renewable resources, and fossil-fueled electrical generators. The continued penetration and intermittency of renewables is challenging the balancing requirements of the Western Interconnect. Integration of renewable resources is impacting the utilization of hydropower and fossil-fueled generators, the latter producing electricity by burning fuels that, as a side effect, emit harmful airborne pollutants and greenhouse gases. The challenge of renewable energy integration and emissions are both issues that hydropower generation could mitigate.

This proposed study considers several scenarios of renewable energy penetration into the electrical grid to which GCD hydropower is connected. These scenarios will consider the rapid development of wind and solar power throughout the Western Interconnect. For each renewable energy scenario, we assume that the GCD power facility has the flexibility – consistent with improvement and long-term sustainability of downstream resources – to operate in response to the variable energy production of wind and solar power. That is, we assume that the GCD hydropower facility is operated to mitigate the disruption to scheduled grid operations caused by

This work may include continued engagement with Project N of the GCDAMP FY 2018-20 Triennial Workplan and with interested AMWG stakeholders regarding the current science and policy regarding dam operations.

the sudden change in supply of electricity produced by wind and solar resources, and subsequent mitigation of emissions throughout the Western Interconnect.

This research will analyze and provide information on:

1. The degree to which GCD operations would change in response to different types and levels of renewable energy penetration in the associated electrical grid;
2. The ability and degree to which GCD can facilitate integration of renewable energy for different types and levels of penetration into the Western Intercontact;
3. The economic damage caused by emissions from fossil-fueled generators under these different scenarios; and
4. The total economic value of hydropower production as a result of GCD's ability to "smooth out" and thus facilitate the introduction of renewable resources and mitigation of emissions.

Reoperation of GCD due to challenges in operation of future electricity sector scenarios could have significant implications for downstream resources and the costs associated with experimental flows. Detailing operations and costs associated with the economic dispatch of hydropower under different energy sector futures is critical to inform adaptive management and the trade-offs associated with future operations and flow experiments.

Western Interconnection cost production modeling will be conducted by the National Renewable Energy Laboratory and CRSP hydropower modeling by Argonne National Laboratory. The GCMRC will lead the refinement of emissions profiles from generation of electricity and the spatial representation and damage estimation of emissions in the Western Interconnect. The modeling of the Western Interconnect and CRSP will be funded by Western Area Power Administration (WAPA). The analysis of emissions profiles and costs will be funded through the Glen Canyon Dam Adaptive Management Program.

In FY 2023, Project N will continue to identify, coordinate, and collaborate with external partners on monitoring and research opportunities associated with operational experiments at GCD designed to meet hydropower and energy resource objectives, as stated in the LTEMP ROD (U.S. Department of the Interior, 2016). This will require the continued coordination between GCMRC, Bureau of Reclamation, WAPA, and other collaborators in the implementation of Project N, including the utilization and development of existing hydropower and regional power system models and data.

4. Budget

Fiscal Year 2021								
Project N	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 14.000%	Total
Budgeted Amount	$32,037	$3,500	$1,500	$0	$18,500	$0	$5,740	**$61,277**

Fiscal Year 2022								
Project N	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 24.000%	Total
Budgeted Amount	$16,499	$1,500	$500	$0	$0	$0	$4,440	**$22,939**

Fiscal Year 2023								
Project N	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 28.000%	Total
Budgeted Amount	$5,665	$1,500	$500	$0	$0	$0	$2,146	**$9,811**

5. References

Bair, L., 2020, Identifying the total economic value of hydropower at Glen Canyon Dam and implications for adaptive management—presentation: Phoenix, Ariz., Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 13, 2020.

Doremus, H., 2011, Adaptive management as an information problem: North Carolina Law Review, v. 89, p. 1455-1498, https://scholarship.law.unc.edu/nclr/vol89/iss5/5/.

U.S. Department of Interior, 2016, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, 22 p. plus appendices, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

Appendix A. Budget Summary

Project	FY2021	FY2022	FY2023
Streamflow, Water Quality, and Sediment Transport	$1,270,000	$1,394,000	$1,468,000
Sandbar and Sediment Storage Monitoring and Research	$1,281,000	$1,197,000	$1,371,000
Riparian Vegetation	$345,000	$395,000	$405,000
Effects of Dam Operations and Vegetation Management for Archaeological Sites	$349,000	$359,000	$363,000
Nutrients, Flow, and Temperature as Ecosystem Drivers	$481,000	$499,000	$509,000
Aquatic Invertebrate Ecology	$797,000	$807,000	$820,000
Humpback Chub Monitoring and Research	$1,780,000	$2,012,000	$1,956,000
Salmonid Monitoring and Research	$828,000	$785,000	$754,000
Invasive Aquatic Species	$619,000	$730,000	$725,000
Socioeconomic Research	$187,000	$222,000	$228,000
Hydropower Monitoring and Research	$61,000	$23,000	$10,000
Geospatial Science, Data Management, and Technology	$543,000	$542,000	$574,000
Overflight Remote Sensing	$1,005,000	$339,000	$374,000
Administration	$1,505,000	$1,674,000	$1,763,000
Total	**$11,051,000**	**$10,978,000**	**$11,320,000**