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Prepared in cooperation with
the Glen Canyon Dam Adaptive
Management Program

Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan Fiscal Years 2021-2023

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

Draft: June 22, 2020

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

Cover: View of the Colorado River in Eastern Grand Canyon below Basalt Creek, Grand Canyon National Park, Michael Moran, U.S. Geological Survey.

RECLAMATION
Managing Water in the West

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

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

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Introduction, June 2020 Triennial Budget and Work Plan Draft

This document represents the latest draft (June 2020) of the Triennial Budget and Work Plan (TWP) and outlines proposed projects and work elements for fiscal years 2021-2023 (FY2021-23) as presented by the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators. It includes revisions to proposed projects outlined in the May 2020 TWP draft in response to the June 15, 2020 review from the Science Advisors Program. Responses to the overall review and specific comments from the Science Advisors as well as responses to feedback to written comments received from Glen Canyon Dam Adaptive Management Program (GCDAMP) stakeholders are not included in this draft of the TWP, but are instead provided as separate documents distributed at the same time as this draft of the FY2021-23 TWP.

The introduction from the May 2020 draft is provided below as a reference of previous activities leading to this draft. In addition to project and work element descriptions, this document includes budget summary tables for each proposed project with cost estimates by project element. Also included are comprehensive tables showing the costs for all projects by year and a summary table that displays total budget estimates by project and year.

The purpose of this document is to continue the discussion with GCDAMP stakeholders, partner agencies, and cooperators about the TWP and attempt to reach consensus on the work to be done by GCMRC and its cooperators in FY2021-23. We look forward to the online meeting with the GCDAMP's Technical Work Group (TWG) on June 23-24, 2020 to discuss the June 2020 draft of the TWP. The GCMRC will incorporate information and recommendations from the TWG and other stakeholders and provide a final draft of the FY2021-23 TWP to the Adaptive Management Work Group (AMWG) on July 29, 2020 for their review in advance of their August 19-20, 2020 meeting.

The final draft of the proposed TWP will contain a summary chapter that includes discussion about how the work plan is responsive to the guidance received from DOI, suggestions provided by the BAHG, TWG, AMWG, and Science Advisors, as well as how it implements the Science Plan for the Long Term Experimental and Management Plan (LTEMP) for the operation of Glen Canyon Dam. This chapter will also include a summary of the administrative history of past guidance to GCMRC from DOI and the GCDAMP as well as a description of the relations between major LTEMP resource and monitoring goals and research themes and each project in the TWP.

Introduction from May 2020 Triennial Budget and Work Plan Draft

This document is a compilation of likely and potential projects proposed to be conducted in fiscal years 2021-2023 (FY2021-23) by the U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators. This Triennial Work Plan (TWP) document contains descriptions of proposed work by the GCMRC during this 3-year period. The TWP also includes budget summary tables for each proposed project with cost estimates by project element as well as comprehensive budget tables for each year of the work plan with all projects and elements included and a summary budget table that includes budget estimates by project and year.

The purpose of this document is to continue the discussion with stakeholders, partner agencies, and cooperators about the monitoring and research priorities that will guide work activities in support of implementation of the Long-Term Experimental and Management Plan (LTEMP) and to meet the scientific information needs of the Glen Canyon Dam Adaptive Management Program (GCDAMP) during the next three years. In addition, this document provides full drafts of proposed work plan projects intended for review and comment by DOI, the Science Advisors Program, Tribes, the Budget ad Hoc Group (BAHG), Technical Work Group (TWG), and other GCDAMP stakeholders.

Each project description includes a list of investigators, a project summary and purpose, hypotheses and science questions, background information, descriptions of proposed work by project element, expected outcomes and products to result from the project, references, and a detailed budget. A number of formal and informal meetings, conference calls, and discussions concerning the FY2021-23 TWP have occurred to date including in-person meetings with Tribal representatives, conference calls with the BAHG, and TWG meetings in January and April. The verbal and written feedback on the extended abstract version of the TWP (shared on April 2, 2020), received by GCMRC thus far, has been informative and helpful as individual investigators worked to develop the ideas into full proposals.

This document identifies likely and potential projects to be funded in FY2021-23. The primary funding source for these activities will be the GCDAMP. Approximately $9.1 million in GCDAMP funding is anticipated to be available to support GCMRC activities in FY2021. A major budgetary challenge for the FY2021-23 TWP is the projected increase in overhead rates for GCMRC due to increased facilities costs associated with a new building. Although delayed for several years, current projections are to move into this yet-to-be built facility in summer or fall of 2022 at which time GCMRC’s lease costs will increase considerably.

Current projections of overhead rates for funds expended by GCMRC are 14% in FY2021, 22% in FY2022 and 28% in FY2023. GCMRC's overhead rates for funds transferred to outside entities will remain at 3% for partner agencies and cooperators and 0% for other USGS science centers although each of these entities typically charge their own overhead rates on funds they expend.

The total cost of all potential projects presently identified by GCMRC for consideration in FY2021 work activities to be funded by the GCDAMP is approximately $10 million. Projected costs of proposed projects in FY2022 and FY2023 are approximately $9.1 million each year. Additional funding to support proposed work beyond anticipated funding levels in FY2021 is proposed to come from several sources.

The cost of the planned 2021 remote sensing overflight is proposed to come from the $225,000 budgeted for this effort in the FY2018-20 TWP and approximately $220,000 in logistics funds not spent in 2020 due to the cancellation of research and monitoring trips because of the COVID-19 pandemic and associated closures of the Colorado River in Grand Canyon and Navajo Nation lands. Additional support for remaining projects is proposed to come from approximately $500,000 in funds projected to be carried forward from FY2020. In FY2021, GCMRC also anticipates applying approximately $216,000 in supplemental funding already received from the Bureau of Reclamation to support monitoring of Lake Powell reservoir water quality to fund activities identified in Appendix 1.

Recognizing the need to reduce project costs from levels identified in the April 2, 2020 draft, GCMRC investigators were directed to prioritize projects and elements focusing first on LTEMP implementation. Criteria identified included determining if the proposed work was necessary to trigger an experiment, for monitoring an ecosystem response, to inform experimental off-ramps, or for context in interpreting responses to experiments. Compliance with the Biological Opinion and National Historic Preservation Act were also priorities. Next level criteria included determining if the proposed work was duplicative and at the appropriate level of effort, included Tribal coordination as appropriate, was logistically efficient, and was of high quality.

Feedback received from stakeholders and others during previously mentioned interactions also proved helpful in providing guidance for identifying areas of budget reduction. To reduce the budget to within anticipated funding levels, GCMRC considered input from partner agencies, cooperators, and stakeholders to identify monitoring and research priorities. GCMRC worked to identify strategies for reducing the costs of specific projects including working with partner agencies and cooperators to eliminate areas of overlap and redundancy and ensure that proposed levels of work did not exceed what is necessary to meet the information needs of decision makers and the GCDAMP and for LTEMP implementation.

It was possible to fund all proposed project elements from the first draft, therefore GCMRC requests feedback regarding the value of those elements that were retained and those that were reduced or removed. We seek input on prioritizing unfunded elements that should be conducted in the event additional resources become available. We look forward to constructive discussions with partner agencies, cooperators, and stakeholders as appropriate as we work to finalize this Work Plan. In June, GCMRC will release a third draft of the proposed TWP which will include final project proposals revised in response to external reviews facilitated by the Science Advisors as well as feedback and comments received on this document from agencies, Tribes, and stakeholders. The third draft of the proposed TWP will also include discussions about how the work plan is responsive to the guidance and suggestions provided by the BAHG, TWG, and Science Advisors as well as how it implements the Science Plan for the LTEMP.

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

1. Investigators

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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 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 Interior, 2016a, b).

The data collected by this project are also used by many 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 data interpretation. 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 to support this network is provided directly to the USGS Arizona Water Science Center from funds appropriated by Congress for the USGS, the Bureau of Reclamation, and the Bureau of

Land Management, and from funds provided by the Arizona Department of Environmental Quality (AZDEQ), the Navajo Nation, and Peabody Energy. Project A is designed to provide measurements of stage (i.e., water-surface 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 press*). The proposed monitoring under this project is similar to that conducted over the last 18 years. Work conducted under the previous workplan, currently provisionally accepted at the Journal of Geophysical Research pending minor revision, indicates that sand storage in the channel and sandbars of the CRe is not likely sustainable unless tributary sand inputs remain well above average and dam releases remain slightly below average. The work proposed in this current workplan is therefore that required to address this important conclusion.

3. Hypotheses and Science Questions

There are two key hypotheses that guide the monitoring and research conducted under Project A. These hypotheses directly address the LTEMP sediment goal and also the nine other LTEMP goals listed in the previous section.

- Glen Canyon Dam can be operated such that the sand resources in the CRe are sustainable.
- Glen Canyon Dam can be operated such that the other CRe resources affected by dam operations can be sustainably managed. In this usage, "dam operations" refers to the amount and quality of the water released from the dam, where "amount" refers to stage and streamflow, and "quality" refers to temperature, salinity, turbidity, and dissolved oxygen.

These hypotheses are paraphrased from the LTEMP EIS and from earlier goals, information needs, and strategic science questions formulated by the GCDAMP. The first of these two guiding hypotheses is tested using the continuous mass-balance sand budgets (element A.3) constructed using 15-minute streamflow data (element A.1) and suspended-sand data (element A.3). Although the second hypothesis guides data collection in Project A, this hypothesis is tested by the other GCDAMP-funded projects.

4. Background

Systematic measurements of streamflow and water quality, including suspended-sediment concentration, in the CRe began with installation of the Lees Ferry gaging station (USGS gaging station 09380000, Colorado River at Lees Ferry, AZ) in May 1921 (Howard, 1947; Topping and others, 2003). During much of the 20th century, daily measurements of suspended-sediment concentration and water temperature, and episodic measurements of other water-quality parameters, were made by the USGS at multiple gaging stations in the CRe and on key tributaries. This intensive period of measurements ended in the early 1970s (Andrews, 1991; Topping and others, 2000a). Concern about the effects of the operation of Glen Canyon Dam on the CRe resulted in a new emphasis on scientific measurements and modeling of water quality and sediment transport beginning in the early 1980s (National Research Council, 1996). The results of these studies have been published in numerous USGS reports and journal articles, and ultimately resulted in the current form of Project A.

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

Suspended sediment is an important water quality parameter in the CRe for several reasons. First, deposition and/or erosion of the eddy sandbars and channel-margin deposits important to many biological, cultural, and recreational resources are directly controlled by the transport of sand (Gloss and others, 2005). The rates of deposition and/or erosion of eddy sandbars and channel-margin deposits are related by mass conservation to spatial gradients in the suspended-sand flux (after Exner, 1920, 1925). By theory (Grams and others, 2013) and experiments (Schmidt and others, 1993), eddy-sandbar deposition is most efficient when the flux of suspended sand is the highest in the main channel of the river. Because suspended-sand flux is the depth-integrated product of suspended-sand concentration and water discharge, maximum main-channel sand flux occurs when the concentration of suspended sand is the highest (determined largely by the water discharge and bed-sand grain-size distribution, e.g., Topping and others, 2007) and the velocity is the highest (i.e., at higher discharge). Under these conditions, the convergence (i.e., negative spatial gradient) in the sand flux between the main channel and the riverbank in an eddy is the largest, leading to the greatest sand deposition rates in an eddy (Topping and others, 2010; Grams and others, 2013). Data collected during HFEs confirmed that eddy sandbars are, in fact, built most efficiently when the discharge is high and the amount of finer sand in a reach is maximized (Topping and others, 2019). Thus, effective management of eddy sandbars and associated resources in different reaches of the CRe requires managers to know when finer sand is maximized in those specific reaches when designing HFEs (Wright and others, 2005, 2008; Topping and others, 2010).

The second major reason as to why suspended sediment is an important water quality parameter is that it largely determines turbidity, and therefore influences the aquatic and fish ecology of the river (Voichick and others, 2016). The endemic fishes of the CRe evolved in a highly turbid river (Gloss and Coggins, 2005). Turbidity is primarily determined by the concentration of suspended silt and clay and, to a lesser degree, suspended sand (Voichick and Topping, 2014; Voichick and others, 2018). Because closure of Glen Canyon Dam cutoff the upstream supply of silt and clay, the post-dam Colorado River in Marble and Grand canyons is much less turbid than ever occurred naturally (Voichick and Topping, 2014). Although on average turbidity increases in a stepwise fashion in the downstream direction (at the mouths of the Paria and Little Colorado rivers), the Colorado River is only highly turbid during periods of tributary flooding (Voichick and Topping, 2014).

The transport of suspended sediment in the CRe is controlled by both the discharge released from the dam and the episodic tributary resupply of sand, silt, and clay (Topping and others, 2000b). The fining of the bed sand in the Colorado River following a tributary flood and the daily increases in discharge caused by dam operations can both cause several orders of magnitude increase in suspended-sand concentration (Topping and others, *in press*). This finding – that sand transport in the post-dam Colorado River was essentially co-equally regulated by changes in discharge and changes in bed-sand grain size (Rubin and Topping, 2001; 2008) – refuted key aspects of the 1995 Glen Canyon Dam EIS (U.S. Department of Interior, 1995, 1996). The 1995 EIS incorrectly assumed that sand transport was regulated only by changes in discharge (Rubin and others, 2002). Owing to the influence of grain size, the residence time of tributary-supplied sand in the CRe is much shorter than assumed in the 1995 EIS (Topping and others, 2000b, *in press*; Rubin and others, 2002; Wright and others, 2005). Thus, the 1995 EIS management strategy – of using multi-year accumulation of tributary-supplied sand for sandbar rebuilding in the CRe during relatively rare HFEs – was not valid (Rubin and others, 2002; Wright and others, 2005). These findings led to the current design of Project A and led to the management strategies for sediment described in the LTEMP EIS, where HFEs are designed on the basis of the availability of tributary-supplied sand (Wright and Kennedy, 2011; Grams and others, 2015).

Sand management in the CRe is challenging because Glen Canyon Dam has cut off almost all of the natural sand supply to the CRe, and the remaining tributary sand supply to the CRe has been declining over time. By cutting off the majority of the sediment formerly supplied to the Colorado River in Marble and Grand canyons, closure of Glen Canyon Dam in 1963 reduced the supply of sand, silt and clay at the upstream boundary of Grand Canyon National Park to ~5% of its pre-dam amount (Topping and others, 2000a). Although other smaller tributaries downstream from the dam do supply sand, silt, and clay to the CRe, the Little Colorado River (LCR) is the largest supplier of silt and clay and the Paria River is by far the largest supplier of sand (Topping and others, *in press*). Though they generally supply only a small fraction of the sand supplied by the Paria River, the smaller tributaries can supply greater amounts of sand during rare years (Griffiths and Topping, 2017). For example, during the Low Summer Steady Flow experiment in summer 2000, House Rock Wash supplied more sand to the Colorado River than either the Paria River or LCR (Schmidt and others, 2007; Griffiths and Topping, 2017). Although the LCR was historically the largest sand supplier, non-climatic changes in the LCR basin from water development and biogeomorphic feedbacks (i.e., channel narrowing and floodplain growth associated with vegetation encroachment) have caused a likely permanent decline in LCR floods and greatly curtailed the delivery of sand to the CRe from the LCR (Dean and Topping, 2019). In addition to its sand-supply implications, this progressive decline in geomorphic disturbance in the LCR has likely negative implications for the spawning habitat of the endangered humpback chub in the lower LCR (Unema and others, *in press*). In addition to the changes in the LCR, an apparent regional decline in winter-spring tributary floods has resulted in the summer-fall season now being the only season of dependable larger sand-supplying events (Topping and others, *in press*). Thus, sand management in the CRe can typically only utilize sand supplied by the Paria River during summer-fall thunderstorms.

Owing to the dual controls of discharge and grain size on sand transport, the sand supplied to the Colorado River during tributary floods migrates rapidly downstream as an elongating sand wave (Topping and others, 2000b, *in press*). The leading edges of these waves migrate downstream at a velocity slightly slower than the velocity of the water. Thus, the leading edges of sand waves exit the CRe within days of a large tributary sand-supplying flood, with this migration rate increasing as a function of discharge. The bed-sand grain-size changes that accompany the migration of these waves cause the sand waves to bifurcate into two packets. The first, leading packet is composed of the finest size classes of sand, is transported as quasi-washload, and is fully transported to Lake Mead within a week of a large tributary flood. The second packet lags the first packet, includes the majority of the sand supplied during a large tributary flood, and migrates downstream more slowly in the Colorado River, taking several hundreds of days to transit the CRe under most dam operations. For example, following large Paria River floods, the finest part of this second packet takes, on average, ~70 days to transit Upper Marble Canyon (above river mile 30) and ~150 days to exit Marble Canyon (Topping and others, *in press*). This result indicates that the most efficient rebuilding of sandbars in Marble Canyon will occur during HFEs conducted within 70 to 150 days after a large Paria River flood.

Project A's measurements indicate that these sand-wave dynamics cause large coupled longitudinal gradients in bed-sand grain size and suspended-sand concentration. As expected on the basis of Exner (1920, 1925), these measured gradients cause net sand deposition in some reaches while they cause net sand erosion in other reaches, with similar longitudinal gradients in bed-sand grain size being associated with larger amounts of either deposition or erosion at higher discharge (Topping and others, *in press*). Thus, owing to downstream migration of tributary-generated sand waves in the CRe, the same dam operation will cause erosion in one reach while it causes deposition in another, with higher dam operations simply causing greater amounts of erosion or deposition in these reaches. Moreover, the locations where any dam operation causes erosion or deposition will change with time as the sand wave migrates downstream. Consequently, sand budgets in the CRe do not generally get more positive in the downstream direction; downstream reaches in Grand Canyon may erode while upstream reaches closer to the dam gain sand and *vice versa* (a key point illustrated in Figure 3 below in our Proposed Work). For this reason, and as a result of a large decline in the LCR sand supply, sand erosion has been recently more prevalent in downstream reaches in Grand Canyon than in Marble Canyon. It is thus fundamentally wrong to assume that monitoring in only Marble Canyon is sufficient to know the status of sand throughout the CRe. Thus, effective CRe sand management cannot utilize empirical relations fit to sparse datasets, but rather requires continuous sand-transport monitoring in key tributaries and at a variety of locations along the Colorado River, as is done in Project A (Griffiths and others, 2012).

Sand management in the CRe is therefore difficult because the tributary sand supply is limited, and sand storage in the CRe is self-limited by the combined effects of grain size and discharge. Although tributary floods supply sand to the Colorado River, these floods also cause the bed-sand grain size to decrease, thereby greatly increasing the downstream transport of sand. Owing to this grain-size effect, tributary flooding causes both sand storage and sand export to increase. Because sand transport increases nonlinearly as a function of discharge, this grain-size effect leads to the retention of less sand in the Colorado River at higher discharge. Consequently, multi-year sand accumulation is only possible in the CRe during years of well-above-average tributary sand supply and below-average dam releases (Topping and others, *in press*). Sand only accumulates in Marble Canyon during years when the Paria River sand supply is >124% of average and annual-mean dam releases are below the post-dam average of 13,700 ft^3/s. Similarly, sand only accumulates in Grand Canyon during years when the combined Paria River and LCR sand supply is >136% of average and annual-mean dam releases are typically well below ~14,100 ft^3/s. In lower sand-supply years, sand is eroded from the CRe during all years where the annual-mean discharge exceeds ~13,100 ft^3/s. Thus, maintaining a level of sand storage sufficient for maintaining sandbars in the CRe may require timing periods of higher and lower dam releases based on the tributary sand-supply conditions. Whether the sand resources of the CRe can be sustainably managed in perpetuity therefore remains an open question.

There is no “short cut” to sediment monitoring in a river like the Colorado River where large changes in sand transport occur independently of the discharge of water; ongoing continuous suspended-sediment measurements are required. Monitoring the CRe therefore requires a strategy where the CRe is divided into reaches on the basis of key tributaries that supply sediment and affect water quality, with continuous monitoring at stations bracketing these reaches (Figure 1). This is the strategy used in Project A since it began in the early 2000s, where the CRe is divided into seven monitoring reaches bracketed by USGS gaging stations. At each of these stations, stage, discharge, water temperature, specific conductance, dissolved oxygen, and turbidity are measured continuously at 15-minute intervals. At the downstream five of these stations in Marble and Grand canyons, suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand grain size are also measured at 15-minute intervals using the methods of Topping and Wright (2016). These streamflow and suspended-sand data are used to compute the sand loads that are, in turn, used in the six user-interactive mass-balance sand budgets served on Project A’s website (Sibley and others, 2015). These sand budgets are used to evaluate the near-realtime continuous effects of dam operations, including special LTEMP releases for invertebrates (i.e., bug flows) and trout management on sand resources throughout the CRe, and used in the design and evaluation of HFEs.

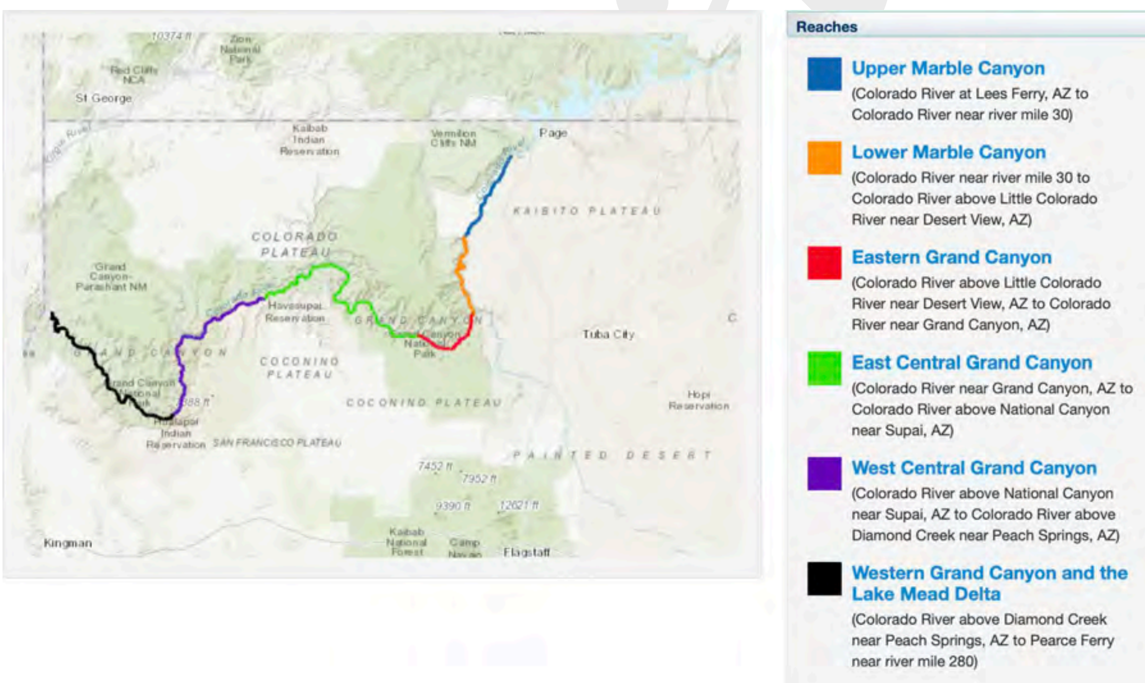

Figure 1. Map showing the extents of the six reaches of the Colorado River in Marble and Grand canyons in which mass-balance sand budgets are constructed. The seventh monitoring reach, lower Glen Canyon, lies upstream from Upper Marble Canyon. Map taken from Project A’s website (U.S. Geological Survey, 2020).

Comparison of our continuous mass-balance sand budgets with topographic-based sand budgets indicates that the mass-balance budgets are accurate at our specified level of uncertainty. Repeat mapping of lower Marble Canyon (river mile 30-61) indicates that 640,000±350,000 metric tons of sand were eroded from this segment between May 2009 and May 2012 (Grams and others, 2019). During this same period, our flux-based sand budget indicates that 690,000±320,000 metric tons of sand were eroded from lower Marble Canyon. In eastern Grand Canyon (river mile 61-87), repeat mapping indicates that 630,000±480,000 metric tons of sand were eroded between May 2011 and May 2014, whereas our flux-based sand budget indicates 690,000±600,000 metric tons of sand erosion. These results from two independent comparisons (i.e., different river segments and time periods) indicate that our continuous mass-balance sand budgets are sufficiently accurate to inform managers of the effects of dam operations on CRe sand resources over timescales ranging from sub-hourly to multiple years.

Only Project A can inform managers of the realtime effect of dam operations on downstream resources in the CRe. As such, the GCDAMP-Technical Work Group approved Project A as Core Monitoring in 2007. Because we collect and serve data at 15-minute intervals, Project A can inform how dam operations affect stage, discharge, water temperature, salinity, turbidity, dissolved oxygen, sediment transport, and sand erosion and deposition in key reaches throughout the CRe on a 15-minute basis. Specific to the LTEMP sediment goal, this capability allows ramping rates and daily ranges to be linked to their effects on sand resources under a wide range of sediment-supply conditions (e.g., during periods of sand enrichment after large tributary floods vs. during periods of sand depletion following extended equalization releases).

5. Proposed Work

The work proposed herein is similar to that conducted under the previous work plan, but at lower cost. Although the data-collection aspects of this project are somewhat reduced, new interpretive products are planned to address the guiding hypotheses and to build on the conclusions of the work funded during FY2017-20. The Project A data-collection network was developed and made progressively more efficient over the last 20 years. It is the cheapest, most-efficient monitoring network required to address the LTEMP sediment goal and support nine other LTEMP goals. This network relies extensively on: 1) new technologies to automatically monitor streamflow, water quality, and sediment; and 2) cost sharing to reduce costs while not sacrificing the data accuracies required by the LTEMP goals.

Research on the Colorado and on other rivers has shown that, to be meaningful, measurements of stage, discharge, water temperature, specific conductance, turbidity, dissolved oxygen, and suspended sediment must be made at temporal intervals shorter than those over which these parameters vary. Owing to the effects of dam operations and tributary floods, substantial changes in all of these parameters occur over timescales less than one hour (Figure 2; Wiele and Smith, 1996; Wiele and Griffin, 1998; Topping and others, 2000b, 2003, 2010; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010, 2014; Grams and others, 2019). Project A was therefore designed to provide measurements of stage, discharge, water quality, and suspended sediment at the required accuracies and sufficiently high temporal resolutions (~15-minutes) to capture the variability in these parameters. Specifically, for suspended sediment, this temporal resolution was chosen to be shorter than the sub-hourly data interval required to know both the sign and magnitude of change in sediment budgets (Grams and others, 2019). Collection of data at 15-minute intervals is the USGS standard. Months to years of data collected at this resolution easily fit on modern dataloggers, result in less processing time in the office, and reduce financial costs to the project. In addition, the efficiencies of such largely automatic data collection require less field time, such that only two river trips are now required annually for this project.

A map showing the locations at which data are collected/utilized by Project A can be viewed at: https://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP. Note that the GCDAMP does not fund the data collection at all stations on this map (see Table 1 below). The data collected/utilized by Project A are used to evaluate the near-realtime effects of all LTEMP dam releases on stage, discharge, water quality, sediment transport, and sediment storage in the CRe (U.S. Department of Interior, 2016a, b). The continuous mass-balance sand budgets provide the measurement-based "ground-truthing" of the Sand Mass Balance Index (SMBI) developed in Appendix E of the LTEMP EIS (U.S. Department of Interior, 2016a). Higher values of the SMBI in the LTEMP EIS were taken as indicators of increased sand storage in the CRe, with increases in sand storage indicating an increase in the sand available to be deposited in sandbars during HFEs. In addition, the sand-transport data and mass-balance sand budgets from Project A are used to trigger HFEs, design the hydrograph of HFEs, and evaluate the effects of HFEs on sand storage in the CRe, as described by U.S. Department of Interior (2016a).

All data collected by Project A are served and can be downloaded at our website at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. At this website, the user can construct plots in time-series or duration-curve format. In addition, the user can construct interactive plots of the mass-balance sand budgets for the six CRe reaches, with user-defined uncertainty.

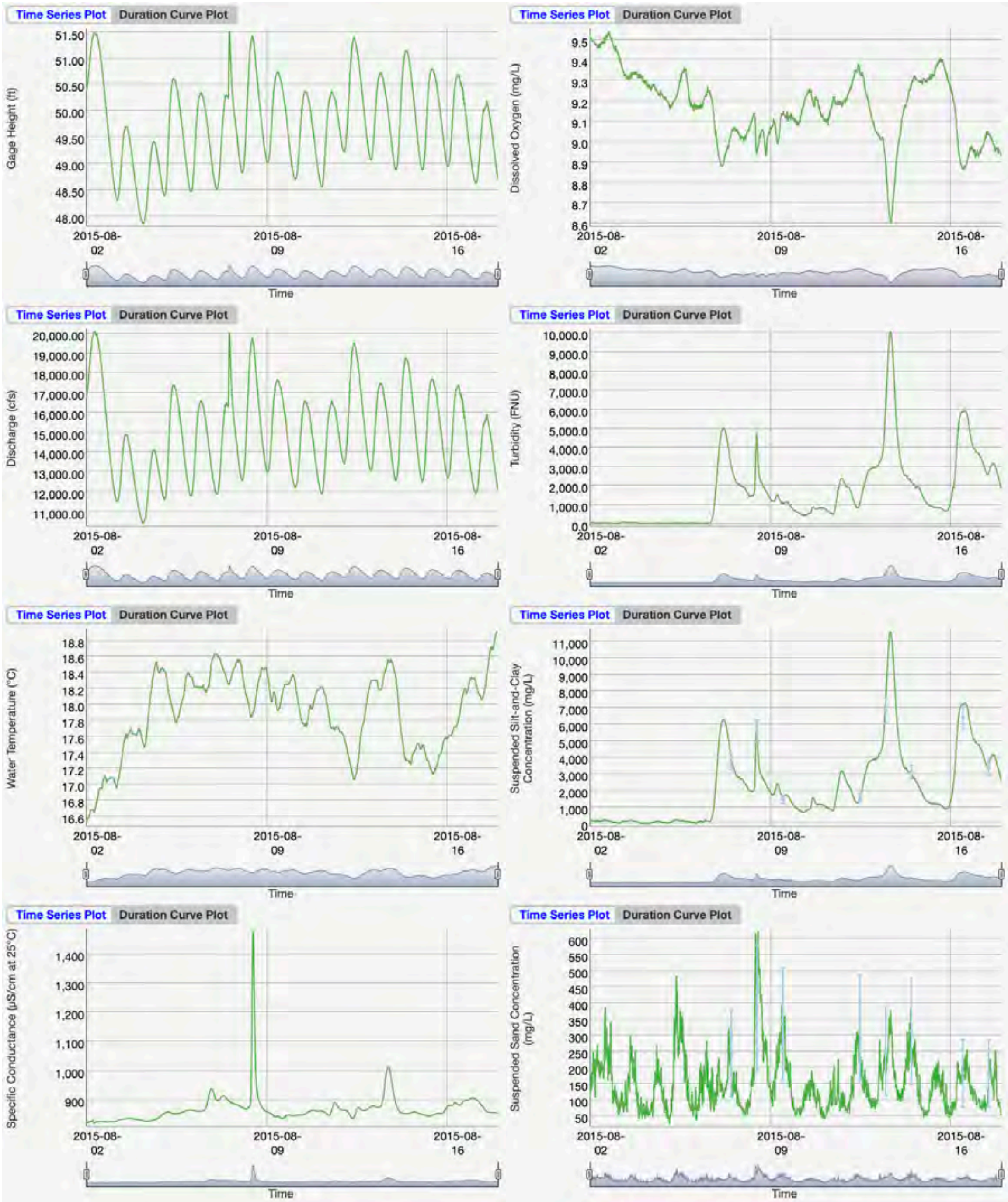

Figure 2. Plots of 15-minute gage height (i.e., stage, water elevation), water discharge, water temperature, specific conductance, turbidity, dissolved oxygen, suspended-silt-and-clay concentration, and suspended-sand concentration for the two-week period 8-2-2015 through 8-16-2015 at the Colorado River above Diamond Creek gaging station. Light blue dots with 95%-confidence-level error bars indicate episodically measured silt and clay concentrations and sand concentrations (from physical suspended-sediment samples) used to verify the two-frequency acoustical suspended-sediment measurements. Variability in each of these parameters over this two-week period arises from the interaction of dam operations with tributary floods. Plots from Project A's website at https://www.gcmrc.gov/discharge_qw_sediment/ (U.S. Geological Survey, 2020).

5.1. Project Elements

The following three project elements fund a large proportion of the salaries of 11 USGS scientists and technicians in the GCMRC, AZ Water Science Center, UT Water Science Center, and OK/TX Water Science Center (database and website), and also fund smaller proportions of the salaries of 12 other USGS scientists and technicians.

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 tributaries. 65% of the budget for element A.1 funds salary for the field and office time required to operate gaging stations and funds the office time for serving data and working on peer-reviewed interpretive publications. Finally, ~6% of the budget in element A.1 is used to maintain Project A's database and website; during FY2021-23, a small amount of this funding will be used to improve download capabilities on the website, including allowing the user to download discharge measurements.

Most of the streamflow data collected under this element are used to support the LTEMP sediment goal, and to design and evaluate HFEs. Of the gaging stations funded by Project A, only the Little Colorado River above the mouth near Desert View, AZ station is not used to support the LTEMP sediment goal; this singular and most-expensive gaging station is used almost solely to support the LTEMP humpback chub goal. The suspended-sand flux is the product of the instantaneous water discharge and suspended-sand concentration. This flux is augmented to account for sand bedload and then integrated over time to calculate the sand load over any given time interval. These loads on the Colorado River and tributaries are used to construct the continuous mass-balance sand budgets described in element 3.

It is impossible to construct these budgets without accurate streamflow gaging stations on the Colorado River and its key sand-supplying tributaries. In decreasing order of their sand-supply magnitude, based on measurements since 2010, these tributaries are: 1) the Paria River, 2) the LCR, 3) the combined smaller tributaries in Lower Glen Canyon and Upper Marble Canyon (RM -15 to 30), 4) the combined smaller tributaries in East Central Grand Canyon (RM 87 to 166), 5) the combined smaller tributaries in West Central Grand Canyon (RM 166 to 225), 6) Havasu Creek, 7) Kanab Creek, 8) the combined smaller tributaries in Eastern Grand Canyon (RM 61 to 87), and 9) the combined smaller tributaries in Lower Marble Canyon (RM 30 to 61) (Topping and others, *in press*). We have therefore designed the Project A gaging-station network to focus resources in a manner appropriate relative to each tributary's importance as a sand source.

We have taken a "burden-sharing" approach to operating the streamflow gaging stations in the CRe owing to insufficient staff at the GCMRC. For example, three of the Colorado River stations are operated by GCMRC staff and three are operated by AZ Water Science Center (WSC) staff. The FY2021 gross costs (including overhead) to the GCDAMP for the surface-water record at each gaging station, the USGS science center operating each station, and the main LTEMP sediment-goal purpose of the streamflow data at each station are listed in Table 1. All gaging stations funded by this element are used to directly address LTEMP goals. Although the streamflow gaging stations on the tributaries do not directly monitor the downstream effects of Glen Canyon Dam operations, these gaging stations are required to monitor the tributary sand supply. Monitoring the tributary sand supply is required to separate the effects of tributary sand-supply events from the effects of dam operations on the sand resources in the CRe. In addition to the collection and serving of stage and discharge data at gaging stations, a large part of the budget for element A.1 supports hydrologic/geomorphic interpretive work in support of the LTEMP sediment, humpback chub, and natural processes goals as described below.

Table 1.

Gaging station	USGS lead	Gross cost to GCDAMP	Main LTEMP sediment-goal purpose
Colorado River at Lees Ferry (RM0)*	AZ WSC	$0	Monitoring sand export from lower Glen Canyon during HFEs and other special LTEMP dam operations
Colorado River near river mile 30 (RM30)	GCMRC	$15,000	15-minute sand loads used in sand budgets
Colorado River above LCR (RM61)	GCMRC	$15,000	15-minute sand loads used in sand budgets
Colorado River near Grand Canyon (RM87)*	AZ WSC	$0	15-minute sand loads used in sand budgets
Colorado R. above National Canyon (RM166)	GCMRC	$7,000	15-minute sand loads used in sand budgets
Colorado R. above Diamond Creek (RM225)	AZ WSC	$20,000	15-minute sand loads used in sand budgets
Paria River near Kanab	UT WSC	$19,000	Flood warning for sampling fieldwork on Paria River at Lees Ferry
Paria River at Lees Ferry *	AZ WSC	$0	15-minute sand loads used in sand budgets
Moenkopi Wash at Moenkopi*	AZ WSC	$0	Flood warning for sampling fieldwork on LCR near Cameron
Little Colorado River near Cameron*	AZ WSC	$0	15-minute sand loads used in sand budgets
Little Colorado River above the mouth**	AZ WSC	$17,000	NONE; used mainly for humpback chub goal
Kanab Creek above the mouth**	AZ WSC	$17,000	Event-based sand loads used to verify sand budgets
Havasu Creek above the mouth**	AZ WSC	$17,000	Event-based sand loads used to verify sand budgets
Eight low-cost research gages on small tributaries in Lower Glen Canyon, Upper Marble Canyon, and East Central Grand Canyon	GCMRC	$8,000 (total for all 8 gages)	Event-based sand loads used to verify sand budgets, and design and evaluate HFEs
Two low-cost research gages on LCR (Grand Falls) and Moenkopi Wash (Cameron)	GCMRC	$6,000 (total for both)	Dean interpretive work investigating declining LCR floods and declining LCR sand supply

*The surface-water records at these gaging stations are entirely funded by non-GCDAMP sources.
**The surface-water records at these gaging stations are partially funded by the USGS toxics program for uranium monitoring.

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. This element also funds episodic measurements of specific conductance associated with suspended-sediment samples collected in tributaries (these measurements are intrinsic to the laboratory methods for processing the suspended-sediment samples and therefore cost nothing). 68% of the budget for element A.2 funds salary for the field and office time required for making the water-quality measurements and funds the office time for serving the data.

All water-quality measurements are made using standard USGS methods. Under this element 15-minute measurements of water temperature, specific conductance, turbidity, and dissolved oxygen are made using YSI multi-parameter sondes in the Colorado River located at the outlet of Glen Canyon Dam and at the gaging stations located at river miles 0, 30, 61, 87, 166, and 225. See Voichick and Wright (2007), Voichick (2008), and Voichick and Topping (2010, 2014) for detailed descriptions of these sondes and measurements. In addition, 15-minute measurements of water temperature are made at three additional stations on the Colorado River and at stations near the mouths of the Paria and Little Colorado rivers, and Bright Angel, Kanab, and Havasu creeks. Finally, ~13% of the budget in element A.2 is used to maintain Project A's database and website.

Data collected under element A.2 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 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. 64% of the budget for element A.3 funds salary for the field, laboratory, and office time required to collect and process sediment data, and also funds the office time for serving data and working on peer-reviewed interpretive publications. In addition, element A.3 fully funds the field component of the phosphorous monitoring of Project E in the Paria River and LCR. The continuous suspended-sediment measurements at the six main-stem Colorado River gaging stations, and the episodic suspended-sediment measurements in the tributaries are all used in the construction and evaluation of mass-balance sand budgets, and are used to trigger, design, and evaluate HFEs.

All measurements funded under element A.3 are made using standard USGS and other peer-reviewed methods. Under this element, continuous two-frequency acoustical suspended-sediment measurements are made in the Colorado River at the gaging stations located at river miles 30, 61, 87, 166, and 225 using the method of Topping and Wright (2016). In addition to informing river management in the GCDAMP, our acoustical method pioneered in the Colorado River is now being used to inform river management across the United States and in Europe. The continuous measurements are used to calculate the sand loads used in sand budgeting, and also used to calculate continuous measures of bed-sand grain size. Because these grain-size values indicate periods of sand enrichment and depletion, they are critical in determining how observed changes in the amount of sand in a reach relate to dam operations. This information allows knowing whether sand erosion or deposition is driven more by dam operations or simply by the longitudinal positions of tributary-generated sand waves in the Colorado River.

In addition to the measurements on the main-stem Colorado River, episodic suspended-sediment measurements are made at the tributary gaging stations funded under element A.1. These measurements are used in conjunction with models (after Topping, 1997) to determine the near-realtime sediment inputs from the Paria River and LCR used in sand budgeting. On the other tributaries, these measurements are used to document the sand, silt, and clay supply from the other major and lesser tributaries and to refine the long-term estimates of the importance of these other tributaries for supplying sediment to the CRe. Most of the sediment work on tributaries utilizes automatic samplers and has a large payoff in information for relatively low cost.

In addition to the collection of the sediment-transport data, this element fully funds the web-based construction and analysis of continuous mass-balance sand budgets for the CRe using the suspended-sediment measurements on the Colorado River and its tributaries (Figure 3). In addition to being used to evaluate the effects of LTEMP dam releases on the CRe, these mass-balance sand budgets are used in collaboration with the Bureau of Reclamation to trigger, plan, and evaluate HFEs (Grams and others, 2015; U.S. Department of Interior, 2016a). HFEs are triggered and designed on the basis of the Paria-supplied sand that accumulates in Marble Canyon during fall and spring implementation windows (U.S. Department of Interior, 2016a). This process involves using many suspended-sediment samples collected in the Paria River (quickly processed through the GCMRC sediment laboratory) in combination with discharge data (funded under element A.1) and initial model estimates (after Topping, 1997) to determine the near-realtime continuous sand supply from the Paria River. The Bureau of Reclamation then uses this information, along with information on planned dam releases, as input to the sand-routing model of Wright and others (2010).

As more suspended-sediment measurements get processed through the laboratory (work funded by this element), the uncertainty is reduced in the calculated Paria River sand supply, and additional model runs are made by the Bureau of Reclamation. As time progresses, the Bureau of Reclamation's model-predictions of sand retention in Marble Canyon are compared against the actual measured sand retention in the continuous mass-balance sand budgets funded under this project element. Because the predictions of the sand-routing model of Wright and others (2010) may be off by a factor of 2, this comparison allows reality-based redesign of each planned HFE hydrograph. Finally, after the completion of each HFE, these sand budgets allow quick post-facto evaluation of the longitudinal effects of each HFE on the sand resources in the CRe in support of the LTEMP sediment goal. Finally, ~8% of the budget in element A.3 is used to maintain Project A's database and website.

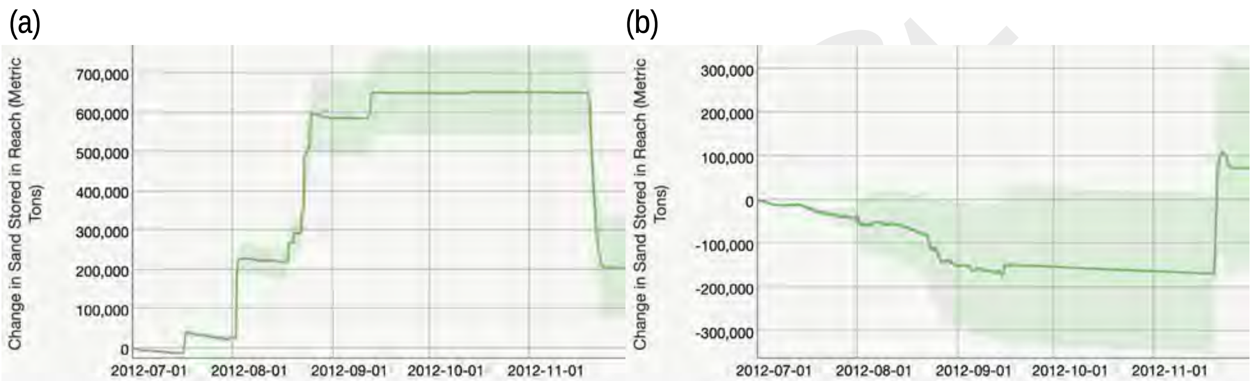

Figure 3. Sand budgets during the 2012 HFE summer-fall sand-accounting interval for (a) Upper Marble Canyon (UMC, river miles 0 to 30), and (b) East Central Grand Canyon (ECGC, river miles 87 to 166). Note that sand accumulated during July-September, 2012, in UMC while it eroded from ECGC. The late November 2012 HFE then partially exhausted the accumulated sand supply in UMC while it caused deposition of sand in ECGC. Plots from Project A's website at https://www.gcmrc.gov/discharge_qw_sediment/ (U.S. Geological Survey, 2020).

Project Element A.4. HFE Experimental Fund

This element funds the collection and processing of streamflow and sediment data before, during, and after HFEs in support of the LTEMP sediment goal. Under this element, crews will be deployed to make discharge measurements and collect suspended-sediment samples at the Colorado River at Lees Ferry, Colorado River near Grand Canyon gaging stations, and also at either the Colorado River near river mile 30 or Colorado River above LCR gaging stations. This work is required to verify HFE effects on sediment.

5.1 Outcomes and Products

Please note that several publications are funded under multiple project elements.

Project Element A.1. Stream Gaging and Hydrologic Analyses

Outcomes:

- Data used to inform LTEMP sediment, 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 goals. Data from this element required to design and evaluate HFEs and to evaluate the effects of all LTEMP dam releases on sediment resources in the CRe. In addition, gaging data on the LCR, Bright Angel Creek, and Havasu Creek used to inform National Park Service humpback chub translocation efforts. Data on all tributaries (including the low-cost gages on the smaller tributaries) used to support Department of the Interior uranium monitoring efforts (thus the cost-sharing support of these gages from the USGS toxics program).

Products:

1) Gage height and discharge data served on the Discharge, Sediment, and Water Quality Monitoring page of the GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/). **NOT FUNDED:** Kanab Creek above the mouth **and either** Havasu Creek above the mouth **or** Little Colorado River above the mouth gaging stations. Temperature data will still be collected at the latter two sites and manually downloaded every six months regardless of which of these two sites receives funding.
2) Journal article evaluating hydrologic changes, especially the decline in winter floods in the Paria River since initiation of gaging in 1923 (Topping lead). These analyses are required to understand how seasonal changes in flooding have affected sand delivery to the CRe and the implications for sediment-triggered spring HFEs (article partially funded by A.3).
3) **NOT FUNDED:** Discharge measurement download tool on the Discharge, Sediment, and Water Quality Monitoring page of the GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/).
4) Data from this element will be used in at least one presentation given by the scientists funded by element A.1 at professional science meetings each year.

Project Element A.2. Continuous Water-Quality Parameters

Outcomes:

- Data used to inform LTEMP aquatic food base, humpback chub, invasive fish species, natural processes, and rainbow trout fishery goals. In addition, water-temperature data on the LCR, Bright Angel Creek, and Havasu Creek used to inform National Park Service humpback chub translocation efforts.

Products:

1) Water-temperature, specific-conductance, turbidity, and dissolved-oxygen data served on the Discharge, Sediment, and Water Quality Monitoring page of the GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/).
2) The chief employee funded by this element will participate as a junior author on articles/reports published by the other GCDAMP-funded projects that use the data collected under element A.2.

Project Element A.3. Sediment Transport and Budgeting

Outcomes:

- Data used to inform LTEMP sediment, archaeological and cultural resources, natural processes, and recreational experience goals. Data from this element required to design and evaluate HFEs and to evaluate the effects of all LTEMP dam releases on sediment resources in the CRe.

Products:

1) Sediment data and sand budgets served on the Discharge, Sediment, and Water Quality Monitoring page of the GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/).
2) Journal article evaluating hydrologic changes in the Paria River since the initiation of gaging in 1923 (Topping lead) (partially funded by A.1; see above text for A.1).
3) USGS Professional Paper evaluating geomorphic and sediment-transport changes in the Paria River basin since the 1800s, with predictions for the most likely future Paria River sand supply to the CRe (Topping lead). This report may be published during the next work plan.
4) Journal article/USGS report describing hydrologic, geomorphic, and sediment-transport changes in Moenkopi Wash, the key source of large floods and sand in the lower LCR (Dean lead). Understanding LCR floods that originate in Moenkopi Wash is critical because these floods are now generally

the largest floods that cause geomorphic disturbance in the humpback-chub habitat in the lowermost LCR. Owing largely to the biogeomorphic feedbacks that have changed the upper LCR (Dean and Topping, 2019), large floods generated farther upstream in the LCR generally attenuate before they reach the lower LCR. Work on this article was begun during the FY2018-20 work plan and will be complete during FY2021.

5) **NOT FUNDED:** USGS report utilizing FY2021 overflight data to evaluate post-2013 travertine dam growth and its implication for humpback chub habitat in the lower LCR (AZ WSC Unema lead). This report would extend the results from Unema and others (*in press*) funded during the FY2018-20 work plan. The LCR is a river in serious decline, with a progressive loss of geomorphic disturbance owing to the decline in peak flows largely caused by the biogeomorphic feedbacks in the LCR ~70 km upstream from the lower LCR humpback chub habitat (Dean and Topping, 2019). Unema and others (*in press*) predicted that the loss of large floods would lead to continued travertine dam growth (potential barriers to chub migration) and travertine cementation of the clean gravels preferred by ripe spawning chub (after Gorman and Stone, 1999). The last comprehensive topographic dataset of the lower LCR available to Unema and others (*in press*) was the topographic dataset from the 2013 overflight. Given that no large floods have occurred in the LCR since before 2013, this proposed report analyzing the changes in the lower LCR between 2013 and 2021 would provide a critical test of the prediction of Unema and others (*in press*) and provide a critical evaluation of the current state and trajectory of the critical humpback chub habitat in the LCR.

6) **NOT FULLY FUNDED:** Journal article describing how sediment-transport in the LCR has evolved since the 1930s, and how the ongoing changes in the LCR basin are likely to affect the future sand delivery from the LCR to CRe (Dean lead). This article may be published during the first year of the next work plan.

7) USGS report describing how all LTEMP dam releases (including possible balancing-tier or equalization releases) conducted during FY2021-23 have affected the sediment resources in the CRe on the reach scale (Griffiths lead). The format of this report will be identical to that being prepared for FY2018-20 (to be published in September 2020).

8) Data from this element will be used in at least one presentation given by the scientists funded by element A.3 at professional science meetings each year.

Project Element A.4. HFE Experimental Fund

Outcomes:

- Data used to inform LTEMP sediment, archaeological and cultural resources, natural processes, and recreational experience goals. Data from this element required to evaluate HFEs.

Products:

1) Sediment data and sand budgets served on the Discharge, Sediment, and Water Quality Monitoring page of the GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/).
2) Interpretation of data collected under this element will be included in the element A.3 USGS report led by Griffiths.

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7. Budget

Owing to efficiencies in conducting the work funded under this ongoing project, and to the diversification of the salary burden to projects on other rivers funded by non-GCDAMP sources, the annual budget proposed for this project during FY2021 is ~9% less than that requested during the FY2018-20 period.

Fiscal Year 2021								
Project A Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
A.1. Stream gaging and hydrologic analyses	$141,130	$4,200	$13,000	$20,700	$0	$96,377	$25,064	**$300,471**
A.2. Continuous water quality parameters	$160,968	$800	$11,000	$20,700	$0	$28,260	$27,085	**$248,813**
A.3. Sediment transport and budgeting	$284,019	$5,000	$42,400	$20,700	$0	$257,260	$49,297	**$658,675**
Total Project A	**$586,116**	**$10,000**	**$66,400**	**$62,100**	**$0**	**$381,897**	**$101,446**	**$1,207,960**

Fiscal Year 2022								
Project A Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							24.00%	
A.1. Stream gaging and hydrologic analyses	$143,952	$4,200	$7,000	$21,300	$0	$98,267	$38,819	**$313,539**
A.2. Continuous water quality parameters	$52,256	$800	$11,000	$21,300	$0	$23,260	$18,778	**$127,394**
A.3. Sediment transport and budgeting	$289,699	$5,000	$37,500	$21,300	$0	$254,060	$77,770	**$685,329**
Total Project A	**$485,907**	**$10,000**	**$55,500**	**$63,900**	**$0**	**$375,587**	**$135,368**	**$1,126,262**

Fiscal Year 2023								
Project A Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
A.1. Stream gaging and hydrologic analyses	$146,831	$4,200	$8,000	$22,000	$0	$100,157	$50,689	**$331,877**
A.2. Continuous water quality parameters	$56,704	$800	$11,000	$22,000	$0	$23,260	$25,341	**$139,106**
A.3. Sediment transport and budgeting	$295,493	$5,000	$37,600	$22,000	$0	$255,860	$100,826	**$716,779**
Total Project A	**$499,029**	**$10,000**	**$56,600**	**$66,000**	**$0**	**$379,277**	**$176,586**	**$1,187,762**

8. Experimental Project Budget

See budget tables in Experimental Project Fund Appendices.

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

As the result of a decline in the funds allocated to Project A and the increasing overhead rate to pay for the new building in FY2022 and FY2023, the funds to the following products and gaging stations have been removed from this proposal. In order of decreasing importance, these unfunded items are as follows.

1) **Element A.3, Product 4:** The proposed Unema and others study and report on the changes to humpback chub habitat in the lower LCR between 2013 and 2021. Please see text in section 5.1 of the Project A work plan for a description of this critical study and report, and a description of why this study and report are important for the LTEMP humpback chub goal. (*$38,000 in FY 2021, $38,400 in FY 2022, $39,000 in FY 2023*).

2) **Element A.1, Product 1:** Kanab Creek above the mouth gaging station. Unless full funding for this gaging station is assumed by the USGS Toxics Program, this action could result in the decommissioning of this gaging station and termination of its long-term temperature record, thus ending the ability to quantify the sediment supply from Kanab Creek (adversely affecting the

LTEMP sediment goal), end knowing the hydrologic and water-quality context of biologic monitoring and research associated with Kanab Creek (adversely affecting the LTEMP natural processes goal), and compromise the Department of the Interior's Grand Canyon uranium monitoring network. (*$17,000 in all three years*).

3) **Element A.1, Product 1:** Havasu Creek above the mouth gaging station or Little Colorado River above the mouth gaging station. Project A has been assigned sufficient funding to support only 50% of one of these gaging stations. The USGS Toxics Program will be assuming the other 50% of the costs of one of these gaging stations. Unless full funding for one of these gaging stations is assumed by the USGS Toxics Program in addition to their already 50% support of the other gaging station, either the Havasu Creek or Little Colorado River above the mouth gaging station will be decommissioned. Decommissioning the Havasu Creek above the mouth gaging station would adversely affect the LTEMP humpback chub goal, the LTEMP sediment goal, and the Department of the Interior's Grand Canyon uranium monitoring network. Decommissioning the Little Colorado River above the mouth gaging station would adversely affect only the LTEMP humpback chub goal because it is of less importance for uranium monitoring, and Project A does not use data from this gaging station for computing sediment loads in the Little Colorado River for sediment budgeting. (*$17,000 in all three years is required to continue either the Havasu Creek or Little Colorado River above the mouth gaging station, depending on which one is funded by the 50% GCDAMP, 50% USGS Toxics support we currently have budgeted*).

4) **Element A.3, Product 5:** Hydrologist salary. Co-PI Dean is currently short salary required for the timely completion of the LCR sediment-transport journal article (*$5,600 in FY 2021, $6,200 in FY 2022, $6,600 in FY 2023*).

5) **Element A.1, Product 3:** Discharge-measurement download tool on Project A website. The discharge measurements made at GCMRC-operated gaging stations and the historical discharge measurements (1921-2018) made at all USGS gaging stations in the CRe are available only through Project A's website. These measurements may currently be plotted but not downloaded at this website. Funding this currently unfunded product would allow for these measurements to be downloaded, and therefore available to the stakeholders, scientists, and the public. (*$20,000 in FY 2022 only*).

Project B: Sandbar and Sediment Storage Monitoring and Research

1. Investigators

Paul Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Matt Kaplinski, Research Associate, Northern Arizona University
Joseph E. Hazel, Jr., Research Associate, Northern Arizona University
Daniel Buscombe, Research Geologist, Marda Science, Flagstaff, Arizona (**not funded**)
Keith Kohl, Geodesist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Robert Tusso, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
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Scott A.Wright, Research Hydrologist, U.S. Geological Survey, California Water Science Center (**not funded**)
Erich R. Mueller, Assistant Professor, Southern Utah University (**not funded**)

2. Project Summary and Purpose

The purposes of this project are to: 1) track the effects of individual high-flow experiments (HFEs) on sandbars and campsites **(funded)**, 2) monitor the cumulative effect of successive HFEs and intervening dam operations on sandbars **(funded)** and sand conservation **(partially funded)**, 3) investigate the interactions between dam operations, sand transport, and channel dynamics **(not funded)**, and 4) develop predictive models for streamflow and sandbar changes that can be used for evaluating dam operations scenarios **(not funded)**.

One of the stated goals in the Record of Decision (ROD) for the Long-Term Experimental and Management Plan (LTEMP; U.S. Department of the Interior, 2016) is to "increase and retain fine sediment volume, area, and distribution...for ecological, cultural, and recreational purposes." Expectations of improved deposition on sandbars and conservation of sediment were among the criteria used in the selection of the preferred alternative. One of the central components of the selected alternative is the continued implementation of HFEs for building sandbars. The LTEMP extended the program initiated with the Environmental Assessment for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam (HFE Protocol; U.S. Department of the Interior, 2011) which asked the question, "Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?" In other words, does the volume of sand aggraded into eddies and onto sandbars during controlled floods exceed the volume eroded from sandbars during intervening dam operations? In addition, condition-dependent experiments were included in the preferred alternative, with objectives related to sandbar building and sediment conservation. Project B includes elements that are designed to evaluate whether the sediment-related goals of the LTEMP are met **(partially funded)**, provide the information that is needed to proceed with or abort LTEMP experimental activities **(funded)**, evaluate the effectiveness of implemented experiments **(funded)**, and develop predictive models for future planning efforts **(not funded)**.

The sandbar monitoring program described here was outlined in the LTEMP Science Plan and provides the data required to answer the fundamental question of the HFE Protocol and LTEMP by monitoring changes in sandbars over many years, including a period that contains several controlled floods. The program is a continuation of the monitoring implemented in previous work plans and is based on annual measurements of sandbars, using conventional topographic surveys supplemented with daily measurements of sandbar change using 'remote cameras' that autonomously and repeatedly take photographs. These annual measurements and daily photographs are included in Project Element B.1 **(funded)**. Because these long-term monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, Project Element B.2 **(partially funded)** includes periodic measurements of nearly all sandbars within individual 50 to 130 km sediment budget reaches (see Project A for description of sediment budget reaches).

The other critical information that is needed to evaluate the outcome of the HFE Protocol and the LTEMP is the change in total sand storage in long river reaches. HFEs build sandbars by redistributing sand from the low-elevation portion of the channel to sandbars in eddies and on the banks. The sand available for deposition is the sand that is in storage on the channel bed, which is the sum of the sand contributed by the most recent tributary inputs, any sand that may have accumulated since Glen Canyon Dam (GCD) was completed, and any sand that remains from the pre-dam era. The goal of the HFE Protocol is to accomplish sandbar building by mobilizing only the quantity of sand most recently contributed by the Paria River, thereby preventing depletion of pre-dam era sand. For this reason, conservation of sand was one of the criteria used to evaluate and select the preferred alternative in the LTEMP ROD. Measured trends in sand storage along the channel bed combined with trends in exposed sandbars will provide the necessary information on which to base future decisions about dam operations and other potential management options. If sand storage is maintained or increased, we expect the response to future HFEs to be similar or better than that observed following recent HFEs. In contrast, depletions of fine sediment in the active channel are potentially irreversible if sand supply from tributaries is consistently less than downstream transport. This situation would threaten the long-term ability to maintain sandbars. These long-term trends are measured in Project Element B.2 **(partially funded)**, which includes two channel mapping campaigns. In 2021, we propose collecting a baseline map for the segment between RM 87 and RM 166, which has never been mapped. In

2023, we propose making a repeat map in Upper Marble Canyon to collect data that will be used in the 10-year assessment of LTEMP to be completed in future work plans. Project Element B.3 includes work on the control network in support of this project, the remote sensing overflight project, and other work plan projects. Project B also includes two research components and several experimental components. The first research component is Project Element B.4 **(not funded)**, which is proposed to investigate river channel adjustment to HFEs and redistribution of reservoir delta sediment on the Colorado River within the Colorado River ecosystem (CRe) in western Grand Canyon. Project Element B.5 **(not funded)** is a modeling project to produce flow models that predict the inundation extent and flow velocities for dam operations and HFEs in Marble Canyon and improve capabilities for predicting sandbar response to dam operations. Project Element B.6 (**Experimental Fund**) describes studies that will be conducted to monitor and evaluate the condition-dependent experiments that affect sandbars and sediment resources, including extended duration HFEs, proactive spring HFEs, and variations in HFE downramp rate.

3. Hypotheses and Science Questions

The sand deposits on the bed and banks of the Colorado River in Glen, Marble, and Grand Canyons are directly affected by the operations of GCD. Depending on the relative magnitudes of dam releases and tributary sediment inputs, sand either accumulates or erodes from the bed of the river. When evaluated over long river segments, sand is evacuated during sustained periods of high dam-releases (Topping and others, 2000; Grams and others, 2015) and sand accumulates during periods of average dam-releases and substantial tributary sediment inputs (Grams and others, 2013; Grams and others, 2018a). Sandbars along the riverbanks above average base flow (about 8,000 ft^3/s) also change in response to dam operations, but in a different pattern, because they are not always inundated and because they comprise a small fraction of the sand in the system (Hazel and others, 2006b; Grams and others, 2013). These deposits aggrade significantly during HFEs that exceed powerplant capacity (Schmidt and Grams, 2011) and, to a lesser extent, during powerplant capacity flows (Hazel and others, 2006b). These deposits typically erode during normal powerplant operations between HFEs (Hazel and others, 2010). Efforts by the Glen Canyon Dam Adaptive Management Program (GCDAMP) to manage fine sediment in this context has resulted in the articulation of goals, information needs, and monitoring needs that were most recently summarized in the Project 3 description of the FY2015-17 GCMRC Work Plan. The following science questions are based on that guidance.

- Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years? (Addressed in B.1 **(funded)** and B.2. **(partially funded)**)

- What is the long-term effect of dam operations, including controlled floods, on the distribution, abundance, and size of eddy sandbars above the 8,000 ft^3/s stage and on total amount of fine sediment stored in the active river channel at low and high elevation?
- How do these changes affect recreation and ecosystem resources such as camping beaches, substrate for riparian vegetation, in-channel backwater habitat for native fish, and areas of bare sand that are redistributed by wind to upslope locations?

- How does the river channel in western Grand Canyon change in response to HFEs and other dam operations? (Addressed in B.4.) **(not funded)**
    - Are there dam operations that exacerbate or mitigate accumulation of sand on the riverbed and affect boat navigation?
    - What are the relative roles of dam operations, upstream sand supply, sediment from eroding banks, and downstream control by Pearce Ferry Rapid in controlling bed elevation and channel dynamics in western Grand Canyon?
- How will any proposed changes in future dam operations scenarios, including the frequency of HFEs, HFE timing, and changes in monthly or annual release volumes, affect sandbars and sand storage? (Addressed in B.5.) **(not funded)**
- Do extended-duration HFEs result in larger or more numerous sandbars than HFEs less than 96-hours long? (Addressed in B.6.) **(Experimental fund)**
- Do proactive spring HFEs provide some mitigation of sandbar erosion in advance of high dam-release water volumes? (Addressed in B.6.) **(Experimental fund)**
- Does decreasing the downramp rate of an HFE result in sandbars with lower beach face slopes and are those sandbars more persistent than sandbars deposited during an HFE with a steep downramp rate? (Addressed in B.6.) **(Experimental fund)**

Relationship between Project Elements and LTEMP Goals

The above science and monitoring questions address LTEMP goals for sediment, recreational experience, archaeological and cultural resources, and tribal resources. Sediment goals are addressed in each of the above questions and monitoring metrics are described in the descriptions for project elements B.1 and B.2. Recreational goals are addressed in project element B.1, which includes measurements of campsite area and the evaluation of campsites by the citizen science Adopt-a-Beach program. Archaeological and cultural resource goals are addressed more directly in Project D, but measurements of the area of bare sand available for transport by wind in elements B.1 and B.2 support that work. Element B.4 contributes to the tribal resources goal by studying how dam operations affect the river channel dynamics in the western Grand Canyon, which is important to Hualapai commercial river operations.

4. Background

The changes to the flow regime and sediment supply associated with completion of GCD (Topping and others, 2000) caused deep scour and armoring of the riverbed in the 25-km reach between the dam and Lees Ferry (Pemberton, 1976; Williams and Wolman, 1984; Grams and others, 2007). Downstream from Lees Ferry in Marble and Grand Canyons, the debris fans at tributary mouths result in a different channel configuration and different style of response to the upstream dam. The boulder and cobble deposits that form rapids have been largely stable (Magirl and others, 2005), while areas of the bed covered by fine sediment have eroded, and many eddy sandbars are much smaller than before flow regulation (Schmidt, 1990; Wright and others, 2005). Because systematic measurements of fine-sediment thickness have not yet been made, the total volume of fine sediment present (or eroded) in Marble and Grand Canyons is not known.

Sandbars are one component of the total sediment budget for the Colorado River. The sediment budget, or sediment mass (or volume) balance, is the accounting by mass (or volume) of all sediment entering and exiting a given river segment.

This budget may be expressed as:

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

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

We use *low* to refer to fine-sediment deposits below the stage associated with the 8,000 ft^3/s discharge and *high* to refer to fine-sediment deposits above the 8,000 ft^3/s stage. The low-elevation deposits are always underwater except during the trough of some flow fluctuations and consist of the lower parts of eddy sandbars and patches of sand on the riverbed. These low-elevation deposits determine the physical characteristics of the aquatic environment, such as the characteristics of backwaters that are used by native fish and are the source for sand remobilized during HFEs. The high-elevation fine-sediment deposits are alternately inundated and exposed, depending on the flow regime. These deposits are used as camping beaches, support riparian vegetation, and support other upland resources.

Annual monitoring of high-elevation deposits has been conducted systematically since 1990. These data clearly demonstrate the role of dam operations, primarily HFEs, in causing changes in sandbar size (Figure 1). Each HFE has resulted in deposition and there has been erosion in each of the periods between HFEs (Hazel and others, 2010; Schmidt and Grams, 2011; Mueller and others, 2014; Grams and others, 2018b). HFEs conducted following the HFE Protocol since 2012 have resulted in sustained, but not progressive, increases in sandbar area (Grams, 2019). Additionally, vegetation has established on portions of sandbars in many parts of the river corridor since the beginning of monitoring (Sankey and others, 2015; Mueller and others, 2018), which may stabilize new HFE deposits so that the extent to which deposition causes increases in the area of exposed bare sand actually decreases.

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

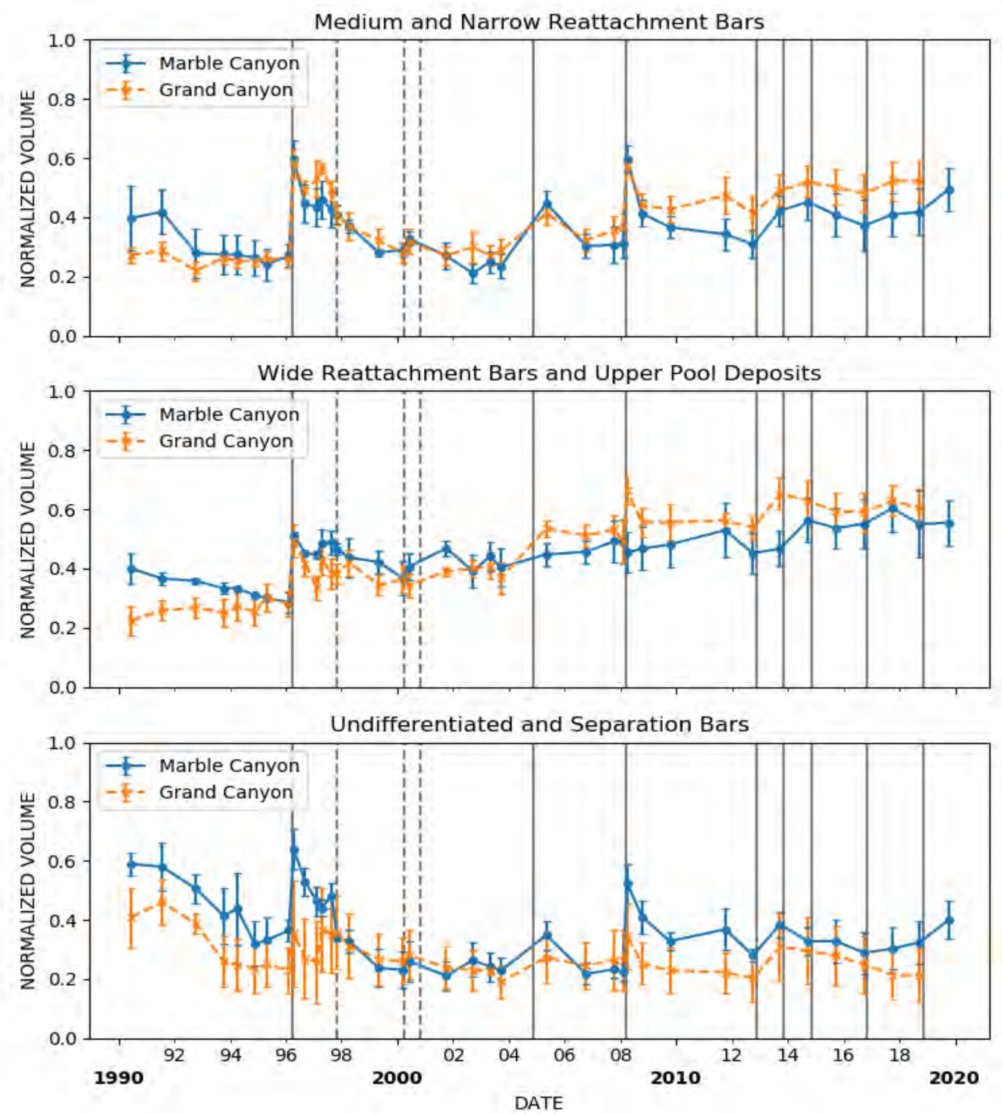

Figure 1. Sandbar size from 1990 to October 2019 (preliminary data provided by Joseph E. Hazel, Jr.). The data are normalized and segregated by bar type, described by Mueller and others (2018).

The measurements of suspended sediment made in Project A track the inputs and outputs (*I* and *O* in equation (1) and are used to calculate ΔS for the sediment budget segments. This approach tracks the accumulation of tributary inputs that is essential for implementation of the HFE Protocol. However, this calculation does not distinguish between low- and high-elevation deposits. Consequently, equation (1) alone cannot be used to evaluate changes in sandbar size, campsite area, sand available for plant colonization, or other changes of recreational or ecological significance. Uncertainty in the measurements of total sediment flux also accumulate with time (see Project A), limiting the utility of those measurements for tracking long-term trends.

Previous studies analyzing repeat topographic measurements of the channel, eddies, and sandbars have found that 90% or more of the changes in sand volume occur at low-elevation, and that high-elevation sandbars comprise only about 10% or less of the fine sediment in the system (Hazel and others, 2006b). These studies have also found that ΔS computed for short study reaches yielded different values than ΔS computed as the difference between sand inflows measured at gaging stations using equation (1). This discrepancy stems from the inability to correctly extrapolate measurements from short reaches to larger spatial scales because changes in bed topography are highly localized and spatially variable (Grams and others, 2013; 2018a). These findings demonstrate that determining whether sediment storage in each storage environment – at low and high elevations and in the channel and eddy – is increasing, decreasing, or stable, and requires repeat measurements of sand storage in a large sample of the storage environments within each of the long sediment-budgeting reaches.

Such measurements have been made in some of the sediment-budgeting reaches since 2009, and repeat maps for both lower Marble Canyon and eastern Grand Canyon capture large spatial variability in erosion and deposition that allow robust calculation of the evacuation of sand that occurred during the period of high releases in summer 2011 (Grams and others, 2018a). These measurements also show an overall loss of high-elevation sand in lower Marble Canyon and a slight increase in high-elevation sand in eastern Grand Canyon. As the period of repeat measurement of the bed and sandbars lengthens, the value of those measurements and the importance of the interpretations will increase.

Figure 2 illustrates how the measurements of bed-sand storage will be interpreted and how they may be used to guide management decisions. This plot shows sand thickness change in sandbars (ΔS_{high}) compared to sand thickness change in the eddy and channel (ΔS_{low}), using data collected in lower Marble Canyon (changes between 2009 and 2012) and eastern Grand Canyon (changes between 2011 and 2014). The measurements for individual eddies show a general tendency for the low- and high-elevation deposits to change similarly, but there are many eddies for which the low- and high-elevation deposits change in opposing directions. Averaged for all of lower Marble Canyon, there was erosion of both low- and high-elevation deposits.

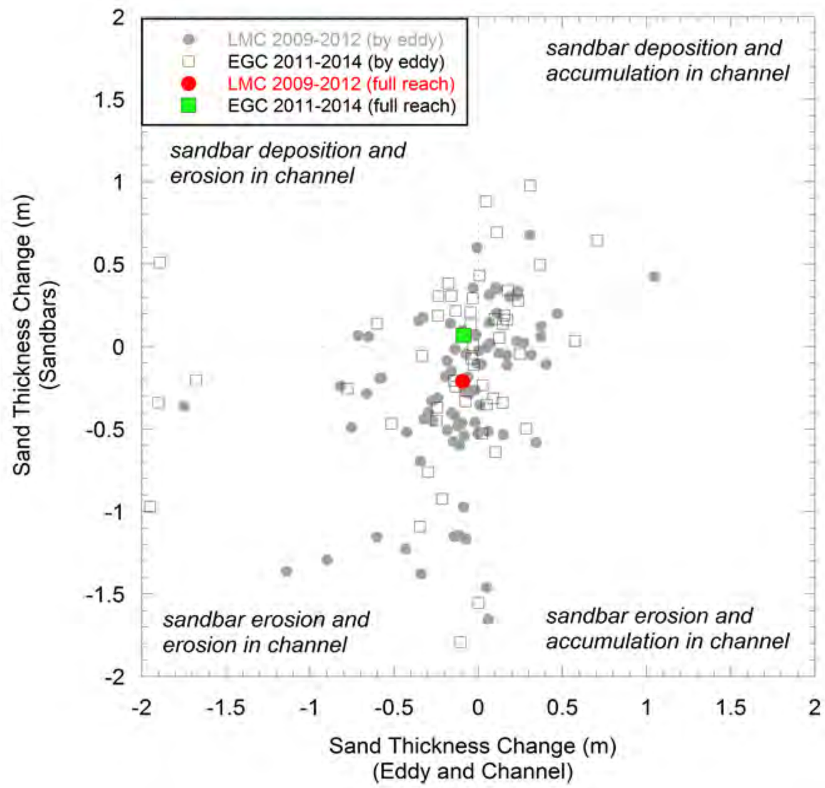

Figure 2. Change in high-elevation sand (sandbars) as a function of change in low-elevation sand (eddy and channel) based on repeat measurements in lower Marble Canyon (LMC) and eastern Grand Canyon (EGC). The data points "by eddy" show changes tabulated for each eddy within the respective reaches. The colored "full reach" points show the average of all changes for each reach. Changes are in average "thickness" of sand. An average thickness change of just 0.5 m over a 50-km reach equates to over 4 million metric tons of sand.

On average in eastern Grand Canyon, there was erosion of low-elevation deposits and slight deposition of high-elevation deposits. If sustained over long periods, these changes would have significant management implications. Sandbar deposition accompanied by accumulation in the channel would indicate that sandbar building and sediment conservation goals are likely being met and, furthermore, that sand supply would likely support increases in HFE frequency and/or duration. Sandbar erosion accompanied by sand accumulation in the channel would indicate that despite adequate sand supply, sandbar maintenance goals are not being met. This would suggest that a change in operations might be required to achieve different results.

Sandbar deposition accompanied by erosion in the channel is expected to occur over short periods (such as during HFEs) as sand is transferred from low to high elevation. However, this pattern of response over long periods would indicate that sandbars are being built at the expense of progressive depletion of sand from the channel. In this case, reductions in HFE frequency and duration or other changes to operations might need to be considered. The "worst case" scenario is erosion of high-elevation sandbars accompanied by erosion of low-elevation sand in the channel.

This is also expected to occur over short time periods, but over long periods would likely indicate that available sand supply is insufficient to support sandbar maintenance without changes in dam operations or other management actions. In summary, if sandbar maintenance goals are not being met and information on low-elevation sand storage is not available, the cause of sandbar declines will be uncertain making it difficult to identify the best management response.

5. Proposed Work

Project Elements

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

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Matt Kaplinski, Research Associate, NAU
Daniel Buscombe, Research Geologist, Marda Science
Robert Tusso, Hydrologist, USGS, GCMRC
Keith Kohl, Geodesist, USGS, GCMRC
Thomas M. Gushue, IT Specialist, USGS, GCMRC

The primary purpose of the sandbar monitoring project is to track the individual and cumulative effects of HFEs and intervening dam operations on sandbars and campsites in the CRe. Information from this project is used to plan and evaluate the effects of LTEMP flow experiments. A subset of all sandbars and campsites located throughout the CRe will continue to be monitored annually using conventional ground-based topographic surveys. These surveys will contribute to the long-term sandbar time-series, which is maintained in cooperation with Northern Arizona University and is the longest, most accurate, and complete dataset describing the state of sandbars in the CRe. The sandbar data and visualization tools are available online at: www.gcmrc.gov/sandbar.

The monitoring program, initiated in 1990, includes surveys at 47 sites, which provides measurements of sandbar area and volume above the stage associated with a discharge of 8,000 ft^3/s. Methods for these surveys are described by Hazel and others (2008; 2010) and Kaplinski and others (2014; 2017). These annual surveys are supplemented by photographs of 42 sites, taken five or more times per day, using autonomous remote digital-camera systems (Grams and others, 2018b). These images make it possible to record the effects of changes in flow at a temporal precision that cannot be resolved by the annual topographic measurements.

The FY2015–17 work plan included a project that evaluated using images collected from hand-held and pole mounted digital cameras for surveying sandbars (Rossi, 2018). The project demonstrated that the method would work but does not provide a time or cost savings over traditional methods. Therefore, we do not propose a change in monitoring methods for this work plan.

The monitoring metrics of sandbar volume and area are related to campsite area (Hazel and others, 2010), but are not a direct measurement of campsite size. Two supplementary monitoring efforts are included in this project to track changes in campsite size that are related to changes in sandbar topography and/or change in the extent of vegetation cover. The first of these project components is annual measurements of campsite area at 32 of the 47 sandbar monitoring sites conducted on the annual sandbar-monitoring trip. The second component is observations and photographs for a collection of approximately 40 of the most popular recreational camping beaches between Lees Ferry and Diamond Creek. These observations are made in a citizen-science project managed by the Grand Canyon River Guides through the “Adopt-a-Beach” (AAB) program. 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 at the time of the 1996 controlled flood experiment (Kearsley and others, 1999).

During the FY2018-20 Triennial Work Plan (TWP), substantial progress has been made on developing and applying machine-learning methods to automatically delineate sandbar area from the remote camera images in cooperation with researchers at Northern Arizona University. Work on this project will continue, with the goal of implementing the method to monitor sandbar size at about a monthly frequency at a subset of the long-term monitoring sites.

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

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The purpose of the HFE Protocol embedded in the LTEMP is to maintain and build sandbars using high flow releases that are timed to coincide with periods of sand supply from tributaries (Wright and Kennedy, 2011). The success of this approach is predicated on the existence of sand within the channel for rebuilding sandbars.

The primary purpose of Project Element B.2 is to track trends in sandbar conditions and sand storage over the time scale of the HFE Protocol and the LTEMP and thereby provide a robust measure of whether or not that supply of sand (the sum of recent tributary inputs and background storage) necessary for building sandbars is increasing, decreasing, or stable (Wright and others, 2008). This project monitors changes in sand storage by location, providing spatially explicit quantification of changes in the channel, eddies and sandbars.

This project element is included in the LTEMP Science Plan and results 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. The information is required to determine whether HFEs should be conducted more frequently or less frequently than prescribed in the LTEMP ROD and will be needed to assess whether the implemented flow regime alone is sufficient to achieve sediment-related goals, or whether additional management actions should be considered.

The sampling design used in this project is based on our current understanding of sediment dynamics, the locations of stream-gaging stations, and the timeframe of the LTEMP. The CRe is divided into seven sediment-budget reaches based on the location of the streamflow and sediment gages (Table 1). For each of the five reaches between Lees Ferry and Diamond Creek, flux-based sand budgets are computed at 15-min. intervals (see Project A). In using these same reach boundaries for long-term sandbar and sand-storage monitoring, we are able to correlate changes that occur in the channel, eddies, and on sandbars with the measurements of sand transport. Because erosion and deposition are spatially variable (Grams and others, 2013), it is necessary to measure approximately 50% to 70% of the channel and eddies within each of these reaches to ensure that the signal in sand-storage change is greater than the noise caused by that spatial variability (Grams and others, 2018a). Because about 90% of the sand that is available for redistribution by dam operations is submerged (Hazel and others, 2006b), the monitoring method must include measurements of sediment on the bed of the river in eddies and pools. Bed sediment data collection will combine multibeam and singlebeam sonars, coupled with conventional topographic surveys for areas above the water surface. These methods have been described by Hazel and others (2008; 2010) and Kaplinski and others (2014; 2017). The data will result in high-resolution Digital Elevation Models (DEMs) of the mapped reaches for each mapping effort (e.g. Kaplinski and others, 2017).

The proposed schedule for completing repeat maps for each reach is based on the major milestones in the high-flow experimental protocol (implemented in 2012) and the LTEMP. These milestones are: 1) 10 years of implementing the HFE Protocol, 2) 10 years after LTEMP implementation when a major evaluation is required, and 3) 20 years after LTEMP implementation.

The assessment of the first 10 years of the HFE Protocol will be based on repeat maps of lower Marble Canyon and eastern Grand Canyon that were collected in the FY2018-20 work plan, and that assessment is in preparation. The 10-year assessment of LTEMP will be provided by repeat maps of upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon conducted between 2023 and 2025 (Table 1). **However, logistics funding for collecting data in upper Marble Canyon in 2023 is not included in this version of the budget; therefore, data from that segment will not be available for evaluating LTEMP.** Repeat maps of west-central Grand Canyon and east-central Grand Canyon will be completed in 2027 and 2028, respectively, to provide interim evaluations of the effects of LTEMP operations on those reaches. The final assessment of LTEMP will be based on repeat maps of all reaches conducted between 2032 and 2036.

Efforts are focused on Marble Canyon and eastern Grand Canyon, because these reaches are believed to have the greatest risk of sediment deficit and because sandbar volume gains in the HFE period since 2012 implementation of the HFE Protocol have not been as large in Marble Canyon as in downstream reaches. However, exclusive focus on Marble Canyon does not fully address sediment-related GCDAMP and LTEMP goals, which include all river reaches in the CRe. For these reasons, an initial map of west-central Grand Canyon was completed in April 2017 and an initial map of east-central Grand Canyon is proposed to be collected in FY2021. Preliminary work on expanding the geodetic control network for this segment was completed in the FY2018-20 TWP (see Project Element B.5). This schedule reduces field activities to one or two mapping campaigns in each three-year work plan.

Because field work is not proposed for 2022, that year will be used for analysis and reporting. Upon completion of a repeat map of a reach, the DEMs will be compared to compute the net change in the volume of sediment within the reach. These computations will distinguish between fine, coarse, and mixed sediment using recently developed acoustic sediment classification algorithms (Buscombe and others, 2014a, b; 2017), between sediment stored in the channel and eddies, and between sediment at high- and low-elevation. The resulting maps of bed sediment substrates are as highly resolved as the bathymetric maps, and therefore can be used for physical habitat classification efforts in other projects. In the past, these applications have included quantifying the relative proportions of sand and gravel that are substrate for aquatic invertebrates (Kennedy and others, 2014), the extent of submerged aquatic vegetation (Project E), and long-term changes in sand abundance (Kasprak and others, 2018).

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

Segment	River Miles	Completed Surveys	Planned Surveys	Repeat Interval
1) Glen Canyon	-15 to 0	2000, 2015	2033	15 to 20 yr
2) Upper Marble Canyon	0 to 30	2013, 2016	**2023****, 2033	7 to 10 yr
3) Lower Marble Canyon	30 to 61	2009, 2012, 2019	2024, 2032	5 to 8 yr
4) Eastern Grand Canyon	61 to 87	2011, 2014, 2019	2025, 2032	5 to 8 yr
5) East-central Grand Canyon	87 to 166	none	**2021***, 2028, 2035	7 to 10 yr
6) West-central Grand Canyon	166 to 225	2017	2027, 2034	7 to 10 yr
7) Western Grand Canyon	225 to 280	none	research only	

* Funding for data collection in east-central Grand Canyon is included in this version of the work plan
** Funding for data collection in upper Marble Canyon in 2023 is not included in this version of the work plan.

Project Element B.3. Control Network and Survey Support

Keith Kohl, Geodesist, USGS, GCMRC
Thomas M. Gushue, IT Specialist, USGS, GCMRC

The purpose of this project element is to provide a geodetic framework to enable high-accuracy change detection and to ensure that geospatial data collected in support of this and other projects are accurately referenced, precisely defined, and can be reliably compared with past and future datasets. In FY2021, we will expand the existing control network into new areas (Project B.4) and provide substantial support to the remote sensing overflight (Project L), archaeological site monitoring (Project D.1), and geospatial science and data management (Project K).

The 2021-2023 planning cycle will include the Nation's implementation of the North American Terrestrial Reference Frame of 2022 (NATRF2022), replacing the North American Datum of 1983 (NAD83) as our official Federal datum. This development requires changing both horizontal and vertical coordinate systems to align with the International Terrestrial Reference Frame. As part of this process, horizontal low-distortion projection systems for the Colorado River through Grand Canyon will be developed and published in an open forum so all prospective users will have access. These grid coordinate systems will be designed specifically for the region and will allow for more efficient data collection, processing, and analysis of areas and volumes.

The new vertical reference system will implement Gravity for the Redefinition of the American Vertical Datum (GRAV-D) data to better realize local height systems, improve geopotential determination of the river system, and monitor geographically dependent changes to the Lake Powell region's gravity over time. Better gravity field models will lead to better understanding of the CRe and more accurate boundary conditions for streamflow modeling. Conversion tools will be implemented to accurately detect geomorphological changes from data referencing the old and new datums (NAD83 and NATRF2022) and new coordinate systems (SPSC1983 and SPSC2022).

We also plan to take advantage of the steady flow conditions that will occur during the remote sensing overflight in 2021 (Project L) to measure an accurate longitudinal profile of the water surface of the Colorado River. These data are required to determine accurate stage discharge relationships throughout the entire ecosystem and will be used to calibrate streamflow models (Project B.5). Although GCMRC has measured accurate water surface elevations and constructed high-quality stage-discharge relations at many locations (Hazel and others, 2006a), a synoptic measurement of the water surface at steady flow has never been made. The only continuous profile of the water surface was measured in 1923 on the U.S. Geological Survey expedition led by Claude Birdseye. Although the measurements made by Birdseye and his team were reasonably accurate, discharge was not steady and ranged from 8,000 to 58,000 ft^3/s on that two-month expedition. The field measurements will be used to ground-truth the overflight data and for streamflow model calibration and verification.

Project Element B.4. Bank Erosion, Bed Sedimentation, and Channel Change in Western Grand Canyon

This project element is currently unfunded. See project element description following the budget section.

Project Element B.5. Streamflow and Sandbar Modeling

This project element is currently unfunded. See project element description following the budget section.

Project Element B.6. Sandbar and River Channel Response to Experimental Actions

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Matt Kaplinski, Research Associate, NAU
Robert Tusso, Hydrologist, USGS, GCMRC
Keith Kohl, Geodesist, USGS, GCMRC
Thomas M. Gushue, GIS Coordinator, USGS, GCMRC

The LTEMP Environmental Impact Statement (EIS) and ROD includes two experimental activities designed to improve sandbar and sediment resources (extended duration HFEs and proactive HFEs) and one experimental activity that may cause increased sandbar erosion (Trout Management Flows). In addition, GCDAMP stakeholders have proposed evaluation of two additional experiments related to HFEs: variation in HFE downramp rate and the effect of HFEs on bed-sediment dynamics in the western Grand Canyon.

The purpose of this project element is to collect and analyze field data on the effects of any of those flow experiments on sediment resources when these experimental dam operations occur. Because the timing of those experiments is condition dependent, the field components would occur only when the experimental dam operations occur and evaluation of the effects of those flow-release experiments is required. **The budgets for these project elements include only the additional costs associated with logistics for field data collection and processing of those data. Analysis and reporting will be absorbed by other Project B elements, as described below.**

Project Element B.6.1. Extended-duration HFEs

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

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

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

The measurements of suspended sand concentration will be used to determine if sand concentrations remain elevated throughout the extended HFE or if sand supply becomes depleted and concentrations decline, and these measurements are included in the regular Project A monitoring. The basis for evaluating the effects of extended duration HFEs on sandbar deposition will be by comparison with measurements of deposition for other HFEs. Images from the remote cameras will be used for a qualitative comparison at all sites and a quantitative comparison at some sites (see Project Element B.1). However, pre- and post-HFE topographic surveys are required for a quantitative comparison with measurements made before and after the 1996, 2004, and 2008 HFEs.

Because the extended duration HFEs are limited to the fall accounting period, data collected in the fall sandbar-monitoring trip, which occurs annually in early October, will be used as the pre-HFE sandbar measurement, which saves logistical costs. One additional sandbar-monitoring trip will be required following the extended duration HFE. The focus of the pre- and post-HFE study will be on deposition above the 8,000 ft^3/s stage. Therefore, the surveys will be for sandbar topography only and do not require bathymetry. Additional information will be gained by conducting daily surveys during the extended duration HFE at two locations. These surveys will allow for comparison between observed sandbar deposition rates and main-channel suspended sand concentrations. Finally, we will compare observed changes in sandbar volume to predictions based on site-specific sandbar modeling (Element B.5) to evaluate the predictive capability of the modeling approach.

Project Element B.6.2. and B.6.3 Proactive Spring HFEs

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

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

This would require surveys of sandbar topography immediately following the proactive HFE and following the equalization flows. Images from remote cameras already in place would be used to monitor the portions of sandbars exposed above water during the equalization flows (see Project Element B.1). The post-equalization flow survey would be accomplished on the annual sandbar-monitoring trip in early October. The post-HFE survey would require one additional survey trip. If river discharge is less than about 16,000 ft^3/s during the survey, this could be accomplished with topography only (Experimental Project B.6.2). If discharge is higher, bathymetric measurements would be required to enable surveying the entire sandbar above the 8,000 ft^3/s stage (Experimental Project B.6.3). Surveying the sandbar down to the 8,000 ft^3/s stage is required for the purposes of comparison with other surveys.

Project Element B.6.4. Variation in HFE Downramp Rate

One of the challenges faced in implementation of the HFE Protocol is a lack of information for predicting sandbar response to HFEs of different magnitude, duration, or hydrograph shape. Although the LTEMP does not describe specific experiments designed to evaluate if/how variation in HFE magnitude or hydrograph shape (ramp rates) may affect sandbar response, experiments that involve adjusting the hydrograph within the parameters of the LTEMP ROD may be conducted.

HFE magnitude and duration are designed based on estimated mass of accumulated sediment in Marble Canyon and limited by facility and operating constraints. Daily measurements of sandbars during the 2008 HFE indicated that deposition occurred for the entire 60 hours of that event. Measurements during the 1996 HFE, which was not sediment-enriched, indicated that deposition rates decreased, and erosion increased after 3 days at peak discharge. Thus, for short-duration (< 96 hour), sediment-enriched HFEs, sandbar deposition is likely maximized by maximizing the time at peak discharge. To maximize the duration of flow at peak discharge, the HFEs have typically been implemented with the maximum allowed upramp and downramp rates. The maximum allowed upramp rate is 4000 ft^3/s per hour and the maximum allowed downramp rate is currently 2500 ft^3/s per hour (prior to the 2016 LTEMP ROD, maximum allowed downramp was 1500 ft^3/s per hour).

The purpose of experimenting with a lower downramp rate is to allow for sandbar reworking and additional sand deposition to occur as the flow decreases. The expectation is that gradual downramp results in sandbars that have a lower slope on the beach face. A sandbar with gradual slope would likely have less total sand volume than the bar with steeper slope but may have larger area above baseflow (~8,000 ft^3/s) discharge. This was observed anecdotally during the 2012 HFE. It is further hypothesized that sandbars with a lower slope will erode at a slower rate and, therefore, persist longer following the HFE. Thus, the hypothesized benefit of decreasing the downramp rate is that the area of usable sandbar above baseflow persists longer, even if the sand volume immediately following the HFE is somewhat less.

The purpose of this experimental project element will be to evaluate those hypotheses if a gradual downramp rate is tested. Addressing these questions will require at least three sets of measurements of sandbar topography at the Project B.1 monitoring sites. The measurements would be collected: 1) immediately following the HFE, 2) approximately 4 months following the HFE, and 3) approximately 10 months following the HFE. These surveys would be used to evaluate the slopes of sandbars created by the HFE and to measure post-HFE sandbar area, volume, and erosion rates. The direct measurements of topography would be supplemented with analysis of images from the remote cameras. Assuming this experiment occurs during a fall HFE, collection of these data would require only two additional sandbar monitoring trips. The third set of data (10 months following the HFE) would be collected as part of the annual Project B.1 sandbar monitoring.

Because HFE duration is based on the time from the beginning of the upramp to the conclusion of the downramp, decreasing the downramp rate means less time on peak discharge for a given duration. For HFEs where the duration is limited by the limited sand supply, decreasing the time on peak may not be desirable. Supply conditions that provide at least 60 hours on peak and a gradual downramp rate would provide the best test of implementing a gradual downramp rate. This could be achieved either with conditions that allow a 96-hour regular HFE or a longer extended duration HFE as defined in the LTEMP EIS.

Project Element B.6.5. Channel Response to Flow Pulse in Western Grand Canyon (not funded)

The purpose of this experimental project element is to collect the field measurements required for the study of channel response to a flow pulse in western Grand Canyon described above in Project B.4. The flow pulse could be a fall or spring HFE or a short-duration pulse of up to 25,000 ft^3/s. The required data are repeat measurements of channel bathymetry and bank topography for the selected 1- to 3-km long study reach. Up to five sets of measurements will be collected: 1) before the flow pulse, 2) once during the flow pulse, 3) immediately following the flow pulse, 4) approximately 1 month following the flow pulse, and 5) approximately 4 months following the flow pulse. Each survey will consist of measurements of the channel with multibeam sonar and measurements of the exposed banks with lidar and/or conventional total station. To prepare for collecting data in the study reach, one additional trip will be made in advance to establish local survey control. As for the other experimental project elements, the budget for this element includes only logistics and personnel expenses associated with data collection and processing and does not include analysis or reporting.

Project Element B.6.6. Trout Management Flows

Trout Management Flows are described in the LTEMP EIS and ROD as repeated cycles of flow fluctuations between high flows of approximately 20,000 ft^3/s and low flows of 8,000 ft^3/s or lower.

The high-flow component would last between two and seven days with the low-flow component lasting for less than 24 hours. These flows are expected to cause increased rates of sandbar erosion. The requirement for monitoring sandbar response would depend on the expected number of fluctuation cycles in a given TMF event. If a TMF event consists of only a few cycles, the increased amount of erosion compared to normal fluctuations would likely be small and difficult to measure. Under this scenario, observations from existing remote cameras will be used to determine if sandbar erosion rates are affected by these flows, particularly at the sites where georectification allows for daily to weekly calculation of area and, potentially, bar volume change. In contrast, if a TMF event consists of many fluctuation cycles, the expected additional erosion might require additional sandbar surveys to quantify sandbar change at all sites. Because we do not know the level of effort that will be required, we have not estimated a separate budget for this experiment.

5.2. Outcomes and Products

Project Element B.1. Sandbar and Campsite Monitoring

- Update at each annual reporting meeting on sandbar area and volume and campsite area based on monitoring from the previous year.
- Annual monitoring data made available on website within six months following data collection.
- Remote camera images showing effects of HFEs made available on website within two months following data collection.
- Adopt-a-Beach photography to be served on website on an annual basis.
- Report and/or journal article on synthesis of Adopt-a-Beach, sandbar monitoring, and campsite data.

Project Element B.2. Bathymetric and Topographic Mapping

- Report and maps for (data release) RM 30 to 87 (mapped in 2019).
- Report and maps for (data release) RM 87 to 166 (to be mapped in 2021). **Reporting on this element may be delayed owing to reduced budget that may delay data processing.**
- Report/journal article on geomorphic changes in lower Marble Canyon and eastern Grand Canyon describing effects of HFE Protocol on sandbars and sand storage, 2009-2019.

Project Element B.3. Control Network and Survey Support

- Publish SPCS2022 grid coordinate systems.
- Toolkit to transform NAD83 data to NATRF2022.
- Update existing GCMRC control database to include new geodetic control measurements and results in NATRF2022.
- Develop an instructional program of protocols for data collection and long-term storage of spatial data.
- Accuracy assessment of remote sensing overflight for inclusion in remote sensing metadata and data release products.
- Report/journal article on the longitudinal profile of the water surface, with evaluation of changes in the profile over time.

Project Element B.6. Sandbar and River Channel Response to Experimental Actions

- Report or journal article describing field data and effects of experimental actions that occur.

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7. Budget

Fiscal Year 2021								
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
B.1. Sandbar monitoring	$141,848	$2,000	$2,000	$25,426	$188,829	$0	$29,643	**$389,746**
B.2. Sediment storage monitoring and research	$156,829	$1,000	$32,200	$109,362	$175,331	$0	$47,175	**$521,897**
B.3. Control network and survey support	$81,954	$1,000	$15,000	$0	$0	$0	$13,714	**$111,668**
Total Project B	**$380,631**	**$4,000**	**$49,200**	**$134,788**	**$364,160**	**$0**	**$90,532**	**$1,023,311**

Fiscal Year 2022								
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
B.1. Sandbar monitoring	$163,436	$2,000	$11,000	$26,011	$208,796	$0	$50,802	**$462,045**
B.2. Sediment storage monitoring and research	$160,236	$2,000	$6,000	$0	$144,497	$0	$41,347	**$354,080**
B.3. Control network and survey support	$58,472	$1,000	$15,000	$0	$0	$0	$16,384	**$90,856**
Total Project B	**$382,144**	**$5,000**	**$32,000**	**$26,011**	**$353,293**	**$0**	**$108,533**	**$906,981**

Fiscal Year 2023								
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
B.1. Sandbar monitoring	$165,218	$1,750	$10,000	$33,622	$191,942	$0	$64,724	**$467,256**
B.2. Sediment storage monitoring and research	$166,996	$1,750	$5,200	$0	$201,570	$0	$54,752	**$430,268**
B.3. Control network and survey support	$59,642	$1,000	$15,000	$0	$0	$0	$21,180	**$96,821**
Total Project B	**$391,856**	**$4,500**	**$30,200**	**$33,622**	**$393,512**	**$0**	**$140,655**	**$994,345**

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

Project Element B.4. Bank Erosion, Bed Sedimentation, and Channel Change in Western Grand Canyon (not funded)

Paul Grams, Research Hydrologist, USGS, GCMRC
TBD, Postdoctoral Researcher, USGS, GCMRC
Matt Kaplinski, Research Associate, NAU
Robert Tusso, Hydrologist, USGS, GCMRC
Keith Kohl, Geodesist, USGS, GCMRC

Proposed budget (note that logistics are a one-time cost covered from the Experimental Fund in element B.6.5):

Project B.4	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 0.000%	Total
FY 2021	$49,796	$1,500	$0	$0	$0	$0	$7,181	$58,477
FY 2022	$47,016	$0	$0	$0	$0	$0	$10,343	$57,359
FY 2023	$48,426	$1,500	$0	$0	$0	$0	$13,979	$63,905

Erosion of sediment from high banks and subsequent remobilization during dam operations, including during HFEs, in the Colorado River arm of Lake Mead Delta presents significant navigation and 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 both this legacy sediment and the sediment continually supplied from upstream.

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. Furthermore, little is known about whether Glen Canyon Dam operations prescribed by LTEMP, including HFEs, affect river channel dynamics in this reach.

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 during a high flow pulse (HFE or release at or near powerplant capacity);

3) Identify potential linkages between river channel change and bed sedimentation to increased sediment supply from banks and lateral channel migration; and

4) Identify whether HFEs, powerplant capacity releases, or other dam operations prescribed by the LTEMP exacerbate or mitigate boat navigation problems associated with bed-sediment accumulation.

We hypothesize that bank erosion rates have increased in recent years as a result of reservoir drawdown and bed incision, and that following initial channel incision, rapid bluff erosion caused bed sedimentation and channel widening which may promote further bank erosion. As bank erosion progresses and the incised river channel widens, we may expect a decrease in sediment supply and a stabilization of the channel planform inset within the delta deposits. In this case, we may hypothesize that vegetation will eventually stabilize bars and form a floodplain inset within the high banks composed of Lake Mead Delta sediments. This sequence of incision, widening, and stabilization has been described for a number of degrading river systems (Simon and Rinaldi, 2006). Changes in reservoir level, changes in the downstream base-level control associated with knickpoint migration, and changes in streamflow and sediment delivery from upstream all affect the rates of these processes and could cause the cycle of adjustment to repeat.

The upstream end of Lake Mead that is within Grand Canyon National Park is the final reach for many Grand Canyon river trips and is the centerpiece of river running operations by the Hualapai tribe. This section of the Colorado River in Grand Canyon is perhaps the busiest section of the river, in terms of boat traffic, in the National Park. It is increasingly difficult for the Hualapai tribe to maintain docks for their upstream fleet, and bed sedimentation often causes boat beaching and difficulty accessing the Pearce Ferry boat ramp. The delta deposits also inhibit natural campground development because there are few beaches adjacent to the steep banks.

The sediments of the Lake Mead Delta extend upstream to approximately the location of Separation Rapid in Grand Canyon, about 40 river miles upstream from Pearce Ferry. Since 2000, Lake Mead water levels have declined approximately 40 meters. The Colorado River has subsequently incised through newly exposed delta sediments, persistently eroding tall banks of fine-grained lake and delta deposits. Erosion of these banks delivers sediment to the river resulting in ever-shifting sandbars throughout much of the lower river corridor between

Separation Rapid and Pearce Ferry. Downstream from Pearce Ferry, the Colorado River flows over a ledge of poorly consolidated bedrock (Pearce Ferry Rapids) because the path of the incised channel does not follow its pre-reservoir course. This ledge (knickpoint) creates a significant navigation hazard and provides the downstream base-level for the incising section of the lower Colorado River in Grand Canyon National Park, and thus plays an important role in regulating incision and sediment evacuation from upstream reaches.

In order to address the primary research questions above, we intend to study channel response to dam operations in a short (~1 to 3 km) study reach (to be selected) downstream from Quartermaster Canyon. We will work with the Hualapai tribe to select a specific reach that is critical for boat navigation. In the first part of our analysis, we propose to use available remote sensing data sets to document historical changes in bank and river channel morphology. The second part of the analysis will include collection of repeat surveys of the riverbed within the selected study reach before, during, and following a dam-released flow pulse. The repeat surveys will allow quantification of the magnitude and spatial distribution of channel morphological change associated with the flow pulse and the return to normal dam operations (field component described in B.6.5). This analysis will be conducted by using the field data to develop a streamflow and sediment transport model for the study reach. The model will allow evaluating bed response in a predictive framework to determine whether there are systematic changes in bed elevation caused by dam operations.

We hypothesize that the flow pulse would transport sediment through and out of the study reach, temporarily scouring a deeper channel that would fill back in upon return to normal operations. The purpose of the study is to determine if this scour occurs and how long the scoured condition persists. We would expect a stronger scour signal with a larger and longer flow pulse. Although we would expect a larger signal to be caused by an HFE, there is value in conducting the experiment around any flow pulse. In either case, the field data could be used to develop and calibrate a flow and sediment transport model. The drawback to conducting the experiment around a smaller flow pulse is that if scour was not observed for that event, it would not mean scour does not occur during larger flow pulses and it may be necessary to repeat the experiment during a larger flow pulse. The advantage of conducting the study around a smaller pulse flow is that if a response is observed, we would learn about how a release that is within the range of powerplant capacity operations might be used to manage sediment in this reach. In order to ensure progress in the study, we propose to collect the field data during the first flow pulse to occur in the FY2021-23 work plan. Thus, if the project is funded and a sediment-triggered HFE occurs in fall 2020, we propose to collect the field data during that event. If an HFE does not occur in fall 2020, we propose to collect the field data during the flow pulse of approximately 25,000 ft^3/s that is currently being planned to occur in spring 2021.

The shifting sandbars of the Colorado River where it flows through Lake Mead Delta sediments presents a considerable navigational hazard. This is an extremely challenging environment for bathymetric mapping because of very shallow and highly turbid water. We will use a very low draft, wide-angle, dual-lidar and multibeam sonar system specially designed for swath mapping in shallow water, collecting swath data up to 10 times the water depth and lidar topography of sediment banks up to 100 m away. Because similar issues exist upstream along the deltas of the Colorado and San Juan arms of Lake Powell, this research project also could provide guidance for management of other large reservoirs in the Colorado River Basin.

Project Element B.5. Streamflow and Sandbar Modeling (not funded)

Paul Grams, Research Hydrologist, USGS, GCMRC
Scott A. Wright, Research Hydrologist, USGS, CAWSC
TBD, Postdoctoral Researcher, USGS, GCMRC
Erich R. Mueller, Assistant Professor, SUU
Matt Kaplinski, Research Associate, NAU
Keith Kohl, Geodesist, USGS, GCMRC
Thomas M. Gushue, IT Specialist, USGS, GCMRC

Proposed budget:

Project B.5	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden 0.000%	Total
FY 2021	$24,898	$0	$0	$0	$12,000	$0	$3,846	$40,744
FY 2022	$47,016	$1,500	$0	$0	$0	$12,000	$10,673	$71,189
FY 2023	$48,426	$1,500	$0	$0	$0	$0	$13,979	$63,905

Predictive models for streamflow and sediment transport developed by GCMRC are used for many purposes within the GCDAMP. Streamflow models are used to predict discharge and water surface elevation, and these predictions are used extensively for both research and planning purposes. Models for sediment transport are used by Reclamation to plan and design HFEs. The first of two streamflow models that are currently in use is the unsteady kinematic-wave flow model of Wiele and Griffin (1997), which is used to predict discharge for steady and unsteady (fluctuating) flows at any river mile location between Lees Ferry and Diamond Creek. This model is incorporated in the Wright and others (2010) sand routing model which is used by Reclamation in HFE planning. The spatial resolution of this model is too coarse for predictions of water-surface elevation at every river mile location. The second model still in use is the model of Magirl and others (2008). This one-dimension streamflow model is calibrated to provide predictions of water surface elevation for steady flow conditions at ~0.1-mile increments between Lees Ferry and Diamond Creek.

Output from this model is currently used by GCMRC to produce maps that predict the inundation extents (shorelines) associated with HFEs or other experimental flows. These models both rely extensively on estimated "synthetic" channel geometry. Because the channel geometry is incorrect, 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 transport or physical parameters such as streamflow velocity. The extensive measurements of channel bathymetry that have been made since 2009 coupled with increases in computing power allow for the development of new streamflow models with substantial improvements in predictive capability. Thus, the purposes of this project element are twofold. The immediate objective is development of a set of models that can be used to predict sandbar response for planning purposes (e.g. analysis of LTEMP operations or scenarios developed in the planning process for new "interim guidelines"). The secondary objective is to develop improved streamflow models that can meet a wide range of research and planning needs. In particular, the improved streamflow model will form the basis of an improved sediment transport model for all grain sizes, including clay/silt, sand, and gravel.

A primary goal of the LTEMP is to increase the size and abundance of sand bars. While annual surveys and remote cameras provide an assessment of changes in bar size, linking physical or numerical models to observed bar response is necessary to provide a framework for evaluating the effects of different flow scenarios. In the FY2015-17 work plan, progress was made on identifying groupings (classes) of sandbars based on geomorphic setting that respond similarly to HFEs and other dam releases, and on developing a simple site-based numerical model (hereafter, morphodynamic model) for predicting sandbar volume changes based on site geometry, measured or modeled streamflow, measured or modeled sand concentration, and physically-based sand deposition and erosion equations. Application of the morphodynamic model requires information on the rates of water (and, therefore, sediment) exchange between the channel and eddy (eddy exchange rate), which can be quantified using 2-dimensional hydraulic modeling. Thus, we propose two linked modeling elements during FY2021-23 to improve capabilities for predicting sandbar response to dam operations, including HFEs:

1) Develop an improved steady and unsteady flow, reach-scale hydraulic model for Marble Canyon using the extensive channel mapping data where available;

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

In FY2015-17 we classified sandbar types based on geomorphic setting using a Principal Components Analysis (PCA) and demonstrated that there are predictable differences in bar response to HFEs and site-scale sediment storage as a function of discharge within the PC-space (Mueller and others, 2018).

The hydraulic modeling will allow us to directly link these differences to the flow hydraulics that control bar sedimentation. We hypothesize that eddies with higher velocities and stronger flow recirculation patterns typical of more narrow reaches tend to be more dynamic and thus potentially more responsive to different flow scenarios and HFE frequency. In lower velocity settings, vegetation encroachment stabilizes sandbar deposits and long-term increases in bar volume reflect the cumulative flow history that may successively increase vegetated bar elevation. This project element will collaborate with Project C to better understand the feedbacks between vegetation encroachment and sandbar dynamics, and how that influences the riparian species guilds associated with different hydraulic environments and inundation frequencies.

We will use bathymetry and near-channel topographic data collected during previous channel mapping trips in Marble Canyon between 2009 and 2016, along with upland topographic data collected in the 2013 aerial overflight, to produce hydraulic models using freely available software packages such as Delft3d or iRIC (i-ric.org) or similar. These numerical models predict flow depth, velocity, and inundation extent (modeled or "virtual" shorelines) from low flows (i.e., < 8,000 ft^3/s) up to the historic flood of record (210,000 ft^3/s). Determining the exact approach will be part of the initial phase of the project. The approach will likely involve both one-dimensional and two-dimensional (i.e., depth-averaged) models. Combined with a recently-developed two-dimensional numerical flow model for Glen Canyon, this work will enable near-continuous predictions of inundation extents and river channel hydraulics, essential for a physically-based sediment transport model that will build upon this hydraulic model to predict fine-sediment (silt/clay/turbidity) transport in collaboration with Project F. These models will represent a substantial advance compared to the existing streamflow models that cannot be used to predict water depths, streamflow velocity, or bed shear stress.

Because hydraulic modeling alone does not simulate sandbar deposition and erosion, evaluating bar response requires a modeling element that couples eddy hydraulics and measured suspended sediment concentration, discharge, and grain size (Project A) to predict sandbar area and volume change. Thus, a primary objective of this research is to use the two-dimensional streamflow model to better parameterize the physically-based morphodynamic model of individual bar response that uses the 15-minute record of flow, stage, sediment concentration, and sediment grain size from any of the gaging stations in the canyon to predict changes in sandbar volume for individual bars or groupings of similar bars. This model directly links the continuous sediment and flow monitoring of Project A with sandbar monitoring using a physically-based approach modified from Andrews and Vincent (2007). The model is constructed to provide predictions of the same monitoring metrics of sand volume and normalized sand volume that are used in

Project Element B.1, which were among the primary metrics used to evaluate and select the preferred alternative in the LTEMP. Model predictions can be validated using the sandbar area and volume data sets, but these validation data sets are at much coarser resolution than the 15-minute model predictions and do not capture the changes in sandbar form that occur between surveys.

As a result, we will use results from the remote camera study (Project Element B.1) to link daily or weekly changes in bar area to the sub-daily predictions of the model. The hydraulic model will enable us to link local hydraulics to the episodic versus gradual erosion processes that dominate following HFEs and quantify site-specific differences in eddy velocity ("eddy exchange rates"). By using modeled eddy exchange rates (from the 2-d hydraulic model) and observed erosion rates (from remote cameras), the model will effectively have fewer free parameters and be a significant advancement over previous modeling attempts that have often involved empirical parameterizations that are not directly related to the processes of sandbar deposition and erosion (i.e. models based directly on flow discharge). Combined with the PCA analysis of sandbar groups (Mueller and others, 2018), we can develop predictions of potential short-term or long-term bar response for sites with differing degrees of bar dynamism and vegetation encroachment under natural or synthetic flow scenarios. Scenario testing will be done in collaboration with Project J.1.

8.2. Unfunded Outcomes and Products

Project Element B.4. Bank Erosion, Bed Sedimentation, and Channel Change in Western Grand Canyon

- Report/journal article on bank erosion, bed sedimentation, and channel response to high-flow experiments on the Colorado River in western Grand Canyon.

Project Element B.5. Streamflow and Sandbar Modeling

- Report, journal article, or data release on the two-dimensional hydraulic model(s), with spatially explicit results, including mapped depth, velocity, and inundation extent (shorelines) for different flow magnitudes.
- Report or journal article on the morphodynamic sandbar model, including original python source code, that couples the streamflow and sediment transport measurements of Project A with the survey and/or remote camera sandbar monitoring data of Project B.1.

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, Associate 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 (Sankey and others, 2015), but favor some species over others. Daily fluctuating flows have been shown to decrease germination and growth of riparian plants (Bejarano and others, 2020; Gorla and others, 2015) 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 cover and composition (Kennedy and Ralston, 2011; Ralston, 2011; Rood and others, 2005). Changes to species proportions and cover result in altered ecosystem functions, since riparian plant species differ in their structure (e.g., tall trees vs. short grasses), morphological traits (thorns, leaf size), and function (shade, soil stabilizer). Through vegetation changes, dam operations can impact wildlife habitat (Ralston, 2005), sediment scour and deposition (Butterfield and others, 2020), visitor experience (Hadley and others, 2018), cultural resources (Cook and others, 2019), and many other natural processes.

The purpose of this project is to monitor the status and trends of riparian vegetation, examine mechanisms behind trends in riparian vegetation change as they relate to LTEMP flows, and apply existing and new knowledge to vegetation management. The four elements of this project assess riparian vegetation status in the CRe (Element 1, **partially funded**), test mechanisms by which flow regime impacts species of interest (Element 2, **partially funded**), synthesize data to anticipate changes to vegetation (Element 3, **funded**), and assist non-flow management actions directed by the Long-Term Experimental and Management Plan (LTEMP) (Elements 2, 3, 4; **funded**, Figure 1). For a description of budget cuts to Project C, see section 8. Elements and Activities Proposed, but not Funded in the Work Plan.

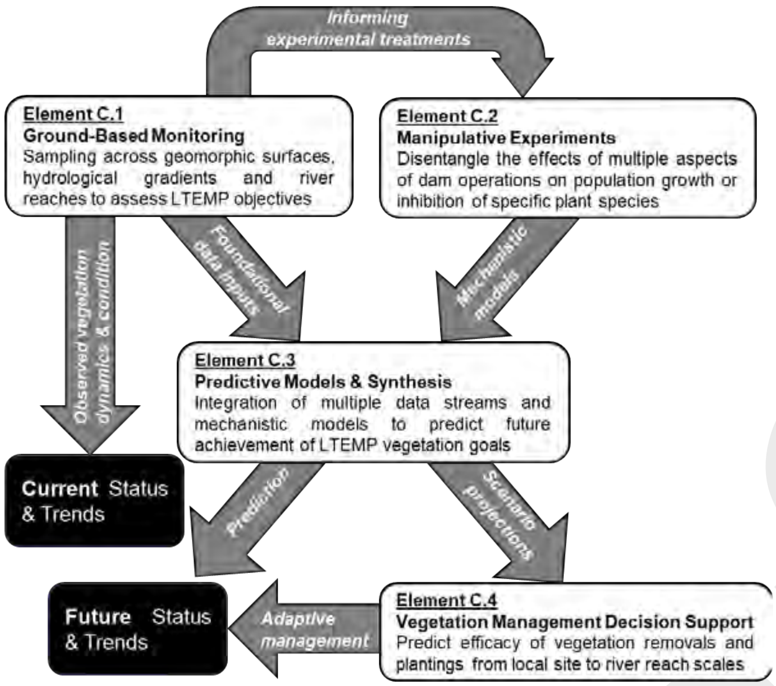


Figure 1. Conceptual diagram of integration among project elements.

3. Hypotheses and Science Questions

This project aims to answer a suite of related research questions regarding riparian vegetation distribution and change and the relationship to flows allowed under LTEMP. These questions were developed to explore the current status of riparian vegetation, the mechanisms instigating riparian vegetation change, and potential methods for improving riparian vegetation management.

- C.1: What is the status (composition and cover) of native and nonnative vascular plant species within the riparian zone of the Colorado River from Glen Canyon Dam to 240 river miles downstream of Lees Ferry?
- C.1: How do dam operations interact with the physical and biological environment to determine vegetation status?
- C.2: How do plant species vary in their adaptations to base flows versus daily fluctuating flows?
- C.2: How can a mechanistic understanding of plant physiological responses to dam operations improve vegetation management outcomes?
- C.3: What are the knowledge gaps in CRe plant ecology, and how can we fill them with existing data sources?

- C.3: What are the predicted changes to CRe vegetation status in the future under current and alternative dam operations?
- C.4: How can existing data be leveraged to assist with experimental vegetation management plans and implementation?

4. Background

River flows are a primary environmental force driving riparian vegetation composition, distribution, and structure (Naiman and Decamps, 1997; Poff and others, 1997). In the CRe, prior research has shown that dam operations can influence the extent and overall areal cover of riparian vegetation (Sankey and others, 2015; Stevens and others, 1995; Turner and Karpiscak, 1980; Waring, 1995), the germination and subsequent dislodging of seedlings through erosion (Porter and Kearsley, 2001), the creation or loss of fluvial marshes (Kearsley and Ayers, 1996; Stevens and others, 1995), and habitat shifts that favor clonal species (Ralston, 2010; Stevens and Waring, 1986). In the CRe, dam operations and surface flows are treated as the primary hydrological driving force for riparian plants, since groundwater levels closely track surface flows (Carpenter and others, 1995; Sabol and Springer, 2013). These studies provided a foundational understanding of generalized plant responses to dam operations that was incorporated into a prototype State-and-Transition model (Ralston and others, 2014). The existing body of literature regarding riparian vegetation in the CRe documents extensive and fairly rapid change in response to dam operations. While no experimental flows have been designed specifically for riparian vegetation management in the CRe so far, all experimental flows conducted have affected this important resource (Melis, 2011; Ralston, 2010; 2011). These dynamic changes need to be tracked, particularly as LTEMP flow experiments are conducted, in order to determine if the LTEMP goals *Riparian Vegetation* and *Natural Processes* are being met. Vegetation monitoring to address this need is described in Element 1.

More recent research has begun documenting that flow induced changes to plants have cascading impacts on other important resources. Vegetation traits are strongly related to inundation (McCoy-Sulentic and others, 2017a) and riparian plant traits are related to fluvial sediment dynamics (Butterfield and others, 2020). Vegetation encroachment on sandbars was identified as a primary reason for both campsite area loss (Hadley and others, 2018) and erosion of cultural sites via the loss of wind-born sand (Cook and others, 2019). These relationships between riparian plants and other resources led to the development of non-flow experimental vegetation treatment actions outlined in the LTEMP. Encroachment by undesirable riparian species is negatively impacting the LTEMP resource goals *Riparian Vegetation*, *Natural Processes*, *Recreational Experience*, and *Archaeological and Cultural Resources*, so is being mitigated by vegetation removals and strategic planting of desirable species (see Reclamation, FY2021-23, C.7 and C.8). Element 1 describes monitoring vegetation on sandbars, while Elements 2, 3, and 4 collectively inform and support experimental vegetation treatments.

Research in the CRe has determined general patterns of plant response to dam operations, as described above, but key information gaps remain that prevent predictions for specific flow patterns and limit our ability to understand how to improve vegetation condition. Recent research in the CRe suggests that species composition is a function of interactions between hydrological variables and climate (Butterfield and others, 2018; Palmquist and others, 2018a). In addition to climate variables, other environmental or biotic variables such as shading, substrate, landform, tamarisk (*Tamarix* spp.) defoliation, and competition likely mediate plant responses to flows. How interactions among these variables influence plant response to dam operations (daily flows and LTEMP experimental flows) is poorly understood and has implications for site choice and success of vegetation management actions. As dam operations and climate change, a solid understanding of how these different variables interact to influence plant composition will be required to adequately manage for the desired conditions listed in LTEMP resource goal *Riparian Vegetation* and support LTEMP vegetation treatments. This is addressed in Element 1.

While increased baseflows support more vegetation close to the river than they did previously, the relative influence of baseflows and daily fluctuating flows on riparian plants is unknown. The influence of daily operations on riparian vegetation has not been evaluated, despite this being the most frequent flood pulse plants experience in the CRe. The few studies that have been conducted elsewhere suggest that daily fluctuations could be reducing the set of species that can grow (Bejarano and others, 2018; Butterfield and others, 2020), reducing establishment of both flood tolerant and intolerant species (Bejarano and others, 2020), reducing physiological processes related to photosynthesis (Gorla and others, 2015), and altering root distributions (Gorla and others, 2015). Additionally, current macroinvertebrate production flows (Project F, “Bug Flows”) could negatively impact some riparian obligate species more than daily fluctuating flows that are not steady on weekends (Gorla and others, 2015). Weekend dry downs could lead to desiccation of riparian species that require a constant water supply, particularly in sandy soils during periods of high evaporative demand. This knowledge gap is key to understanding how daily operations are influencing the LTEMP resource goal *Riparian Vegetation* and is addressed in Element 2.

The flood and drought tolerances of many common CRe plant species are unknown or poorly studied. Species that are increasing on camping beaches and along the river’s edge, such as arrowweed (*Pluchea sericea*) and Emory’s baccharis (*Baccharis emoryi*), have rarely been studied. A basic understanding of how these species respond to flood and drought stress will increase our ability to understand responses to dam operations. This line of research has direct implications for LTEMP goal *Riparian Vegetation*, the responses of these species to LTEMP experimental flows, and LTEMP vegetation treatments and is addressed in Element 2.

The range of historic and current flows within the CRe does not encompass the full range of flow variability of the future. Since all studies and data that have been conducted thus far in the CRe are based on that subset of flows, predicting vegetation responses to future flow scenarios is quite limited. Developing more detailed predictive models using the existing State-and-Transition model, local and regional riparian monitoring data, and large national and global databases, will increase the ability to predict changes to LTEMP resource goals under future flow scenarios. These efforts are described in Element 3 and would model outcomes regarding the LTEMP resource goal *Riparian Vegetation*, with consequent implications for *Natural Processes*, *Recreational Experience*, and *Archaeological and Cultural Resources*.

LTEMP experimental vegetation treatments are collaborative in nature and adaptive in process. As vegetation removals and plantings are planned, conducted, and evaluated, project partners will need research products to inform their next steps. The products listed in Elements 1, 2, and 3 can all be leveraged to inform this work. Element 4 describes the nature of this collaboration.

5. Proposed Work

5.1. Project Elements

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

Emily Palmquist, Ecologist, USGS, GCMRC
Brad Butterfield, Associate Research Professor, NAU, ECOSS

While riparian vegetation ties into many of the LTEMP goals, two are entirely or substantially related to riparian vegetation cover and composition: *Riparian Vegetation* and *Natural Processes*. The first goal requires regular assessment of the types and cover of riparian vegetation along the length of the river corridor and across landscape features. The second goal requires detailed, concurrent measurements of how riparian vegetation is altering and being influenced by geomorphic processes. This project element collects two related datasets to address the different aims and scales of these goals. 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. This ground-based monitoring forms the basis of vegetation status and trends reporting, and the backbone for analysis and modeling efforts. Stratified-random sampling of multiple geomorphic features provides a thorough assessment of vegetation composition, cover, richness, and native to nonnative species dominance throughout the CRe. Different riparian vegetation communities are associated with different segments of the river, so monitoring in one segment does not represent vegetation change in all of the CRe (Palmquist and others, 2018a). Riparian vegetation composition also varies by geomorphic feature and distance above base flows (Figure 2) (Butterfield and others, 2018; 2020). Due to budget constraints, and in response to stakeholder requests to consider reduced frequency of monitoring, the work proposed here is not annual sampling of both datasets. Rather, sampling of multiple geomorphic features is scheduled for FY2021 and FY2023, and the long-term monitoring sites in FY2021 and FY2022. This work was previously conducted for both types of monitoring on an annual schedule. The shift from annual sampling to alternate year sampling will further limit our abilities to correlate observed vegetation change to LTEMP flow experiments, especially if those experiments occur during sampling off years. It will still provide information regarding the state and overall trends of riparian vegetation through time.

Daily and experimental flows may differentially impact the cover and composition of these different riparian plant communities. To quantify if riparian vegetation is “diverse, healthy, productive, self-sustaining, and ecologically appropriate” (U.S. Department of Interior, 2016) across environmental gradients, approximately 100 sample sites are sampled in the fall between river miles -15.5 and 240. During this workplan, these measurements are funded for FY2021 and FY2023 only. Sampling incorporates multiple geomorphic features and spans a hydrologic gradient, including the area influenced by high flow experiments. This dataset tracks if the *Riparian Vegetation* goal is being met.

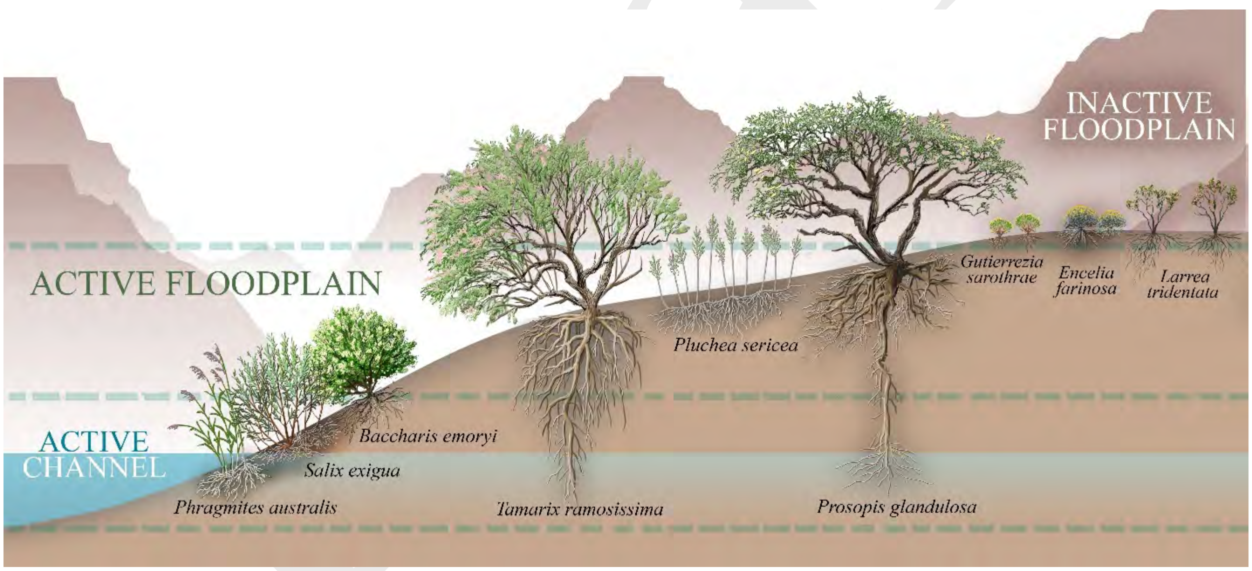


Figure 2. Illustration of where common plant species of the CRe typically grow in relation to the river. Plant species are commonly arrayed along a hydrological gradient with more flood-tolerant species growing closer to the river. Image credit Victor Leshyk.

Vegetation and topographic surveys at long-term monitoring sandbars and campsites provide an opportunity for integration of vegetation and sediment dynamics and a more focused assessment of the impacts of vegetation on recreational resources. Riparian vegetation both influences and is influenced by sediment deposition (Butterfield and others, 2020; Gurnell, 2014). Plants will grow on newly deposited sand and stabilize the surface. When another sediment-laden flood moves over the sandbar, sediment deposition is altered by vegetation (Figure 3). Species interaction with sediment deposition is influenced by physiological and morphological traits of the species (Butterfield and others, 2020; Diehl and others, 2017). Species composition and density, then, is important to sandbar evolution and shape. By collaborating on the topographic surveys conducted in Project B.1, this data set contributes to evaluating the *Natural Processes* goal in the CRe. Vegetation sampling is conducted at the same time as topographic surveys on 43 sandbars. The vegetation plots are included in the topographic survey, so that detailed flow parameters can be tied to recorded vegetation composition and cover. In this workplan, the vegetation component of this sampling is funded for FY2021 and FY2022 only. Any alterations to the sampling schedule will be coordinated with Project B.1.

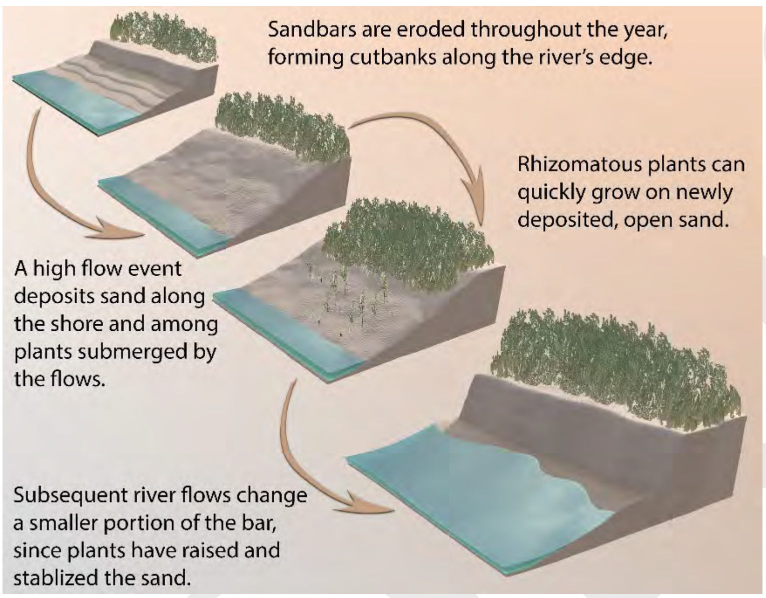


Figure 3. General characterization of sandbar stabilization by riparian plants. Image credit Emily Palmquist and Victor Leshyk.

Plant species that comprise riparian vegetation germinate, grow, and die at different timescales and under different environmental settings. A given flow event, such as a flood, can have a positive influence on some species (for example, seeds stimulated to germinate) and negative influence on others (for example, flood waters suffocate non-flood adapted species) (Stromberg and others, 1993). Some species will respond within a few weeks, while others may take a year or more to respond, depending on their life history traits and the parameters of the flow event. Additionally, compounded flow patterns may initially promote some species, then stress them (Gómez-Sapiens and others, 2020), like low flows that support seedling growth followed by an erosive spike-flow (Porter and Kearsley, 2001). In the last five years, monitoring data has recorded annual changes in the amount of vegetation growing close to the river (Butterfield and others, *in prep*), documenting that riparian vegetation in the CRe is capable of rapid change. While it is well understood that riparian vegetation in general has expanded in overall cover over since 1965 (Sankey and others, 2015), changes to specific species of interest and on shorter time scales needs further research. The original annual timescale of this monitoring program was designed to address these shorter term and variable vegetation changes, but even annual measurement is not frequent enough to evaluate immediate impacts and mechanisms of change from specific LTEMP experimental flows. This limitation is addressed using experiments in Element 2.

The methods for this monitoring program were formally compared to other vegetation sampling methods, peer-reviewed, published, and available online (Palmquist and others, 2018b; 2019). In short, at selected sampling sites, 3 to 6 transects are run perpendicular to the shoreline. Along each transect, 9 one-meter square frames are surveyed. These frames are stratified among three hydrological zones that represent the area inundated by flows up to 25,000 cfs (active channel), up to 45, 000 cfs (active floodplain), and pre-dam flooding. Ocular cover estimates are given to each species present in the sampling frame, as well as total foliar cover and multiple ground cover elements (for example, rock, sand, litter). This monitoring is intended to be complementary to imagery-based vegetation monitoring conducted at longer timescales and for common plant species (see Project L). The imagery collected as part of Project L derives estimates of total area covered by vegetation and common, canopy species on a longer time scale. Previous digital, 4-band multispectral imagery datasets were collected in 2002, 2005, 2009, and 2013, with the next dataset scheduled to be collected in 2021. The monitoring described here provides a shorter time frame, fine-scale measurements for many more species (over 300) and assesses cover of species growing underneath the canopy. Together, these datasets monitor the breadth of riparian vegetation change in the CRe.

Collaboration with the National Park Service (NPS) Northern Colorado Plateau Network Inventory and Monitoring Network (NCPN) will continue. This valuable collaboration has existed for the duration of the current monitoring program (starting 2013). By using two field technicians employed by NCPN, data are collected by highly skilled botanists for only the necessary time period (a few weeks once a year). This maintains data quality standards while reducing costs. Additionally, this collaboration facilitates communication across vegetation programs in the Colorado River Basin and provides an opportunity for future basin-wide data analysis.

This unique dataset consists of a robust set of sample points that span many well measured environmental gradients. Since the CRe is one of the most intensively studied river systems in the world that is naturally environmentally variable with a relatively consistent flow regime, this monitoring dataset provides a unique opportunity to evaluate if and how environmental variables interact to shape riparian plant communities. For example, preliminary analyses using this dataset suggest that in locations with more insolation (less shade), riparian plants grow closer to baseflows. The influence of hydrological variables may shift under different conditions, like increasing in importance under warmer climates. We propose to use these monitoring data to evaluate how the influence of hydrological variables changes under different environmental conditions and assess whether these interactions change over different scales and as temperature increases.

Linear or non-linear regression in a hierarchical Bayesian framework will be used to combine the many existing datasets to test for correlations among variables. This analysis is appropriate for this goal since the data is inherently hierarchical, includes missing values, and has variables sampled at different spatial scales.

Project Element C.2. Determining Hydrological Tolerances and Management Tools for Plant Species of Interest

Brad Butterfield, Associate Research Professor, NAU, ECOSS
Emily Palmquist, Ecologist, USGS, GCMRC

Base flows and daily fluctuating flows both influence the composition of riparian vegetation within different hydrological zones in the CRe. High-Flow Experiments (HFEs) influence vegetation by depositing sand at different elevations, thereby creating habitats with varying depths to the water table (Butterfield and others, 2018). The separate effects of base and daily fluctuating flows on vegetation cannot be determined from observational monitoring alone because they are highly correlated: lower habitats are closer to base flows and experience greater magnitude daily fluctuations than higher elevation habitats. Experiments are therefore necessary to independently vary these factors in order to disentangle their independent and interactive effects on vegetation composition.

The primary objective of this project element is to identify the aspects of dam operations that have led to the expansion of populations of particular species and the absence of other desirable species from the CRe. We will achieve this objective through an understanding of the impacts of drought, inundation and fluctuations in these factors on plant physiology and growth.

The secondary objective is to incorporate these experimental results into the dynamic vegetation models detailed in Project Element C.3 below. The PIs of this project will be assisted by an undergraduate summer intern in each year through the Northern Arizona University (NAU) Research Experience for Undergraduates program, funded by the National Science Foundation. This program recruits primarily from Tribal colleges, and we will be reaching out to stakeholders to identify interested students to engage in this program.

We propose to achieve these objectives through manipulative experiments in mesocosms under controlled conditions outdoors at the NAU Research Greenhouse Complex. By identifying physiological constraints on plant performance related to dam operations, we will address the following specific management questions:

- How do hydrological adaptations of the dominant species in the CRe influence their responses to current and future dam operations?

- What are the hydrological drivers of recent expansions of certain species, and low success of others? How can the answer to this question inform management?

These questions will all be addressed through the same series of experiments, the first focusing on a large suite of species, the second narrowing in on three species of interest: Goodding's willow (*Salix gooddingii*), a species with cultural, recreational and wildlife value that has shown limited success in restoration treatments in the CRe; arrowweed, a clonal species that has greatly reduced viable camping area on high value recreational beaches; and seepwillow, a genus of large shrubs that has increased near the channel, altering recreational and wildlife behavior at the interface between terrestrial and aquatic habitats.

Flood and drought adaptations

Plants can respond to stress through tolerance, acclimation or both. This provides some remarkable symmetries for considering plant responses to both flooding and drought (Figure 4). Plants initially respond to both stressors by reducing stomatal conductance – transpiration of water from pores in the leaves that is necessary for photosynthesis. In response to drought, reduced stomatal conductance helps plants avoid embolisms by keeping leaves, stems and roots from experiencing dangerously negative pressure potentials that occur when soils become dry (Bartlett and others, 2016). In response to flooding, reduced stomatal conductance is a sign of impaired root function due to anoxia (Kreuzwiese and others, 2004). Acclimation to drought and flood stress both include root growth, albeit in different ways: plants can develop deeper root systems with access to more persistent moisture to tolerate a declining water table (Horton and others, 2001); in response to flooding, some plants are capable of developing new, adventitious roots above their previous root system, providing access to more oxygenated conditions and creating new kinds of tissues called aerenchyma that allow for recovery of oxygen transport (Copolovici and Niinemets, 2010). These responses can be quantified in real time through changes in stomatal conductance in response to persistent changes in moisture or oxygen availability to roots, and through examination of root development following these changes.

Our overarching hypothesis is that mechanisms of drought and flooding tolerance are critical for adaptation to daily fluctuating flows, whereas reliance on acclimation mechanisms result in mal-adaptation. This hypothesis follows from the fact that acclimation mechanisms occur at a slower timescale than the frequency of daily fluctuating flows, making it difficult for species depending on new tissue development to acclimate to daily fluctuations. For example, development of adventitious roots could be beneficial during daily peak flows, but suffer damage during daily low flows; likewise, development of deeper roots can be advantageous during daily low flows, but become anoxic and die during daily peak flows. Instead, plants that can maintain metabolic activity under dry and/or anoxic conditions should be better at tolerating daily fluctuations.

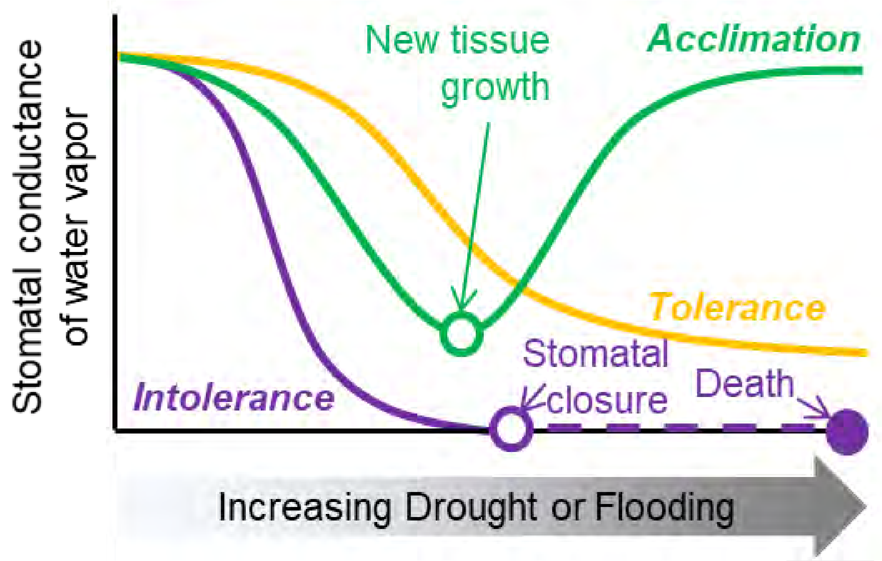


Figure 4. Modes of plant response to drought or flooding. Plants can either tolerate stress, resulting in only a moderate reduction in physiological function (indicated by stomatal conductance), acclimate to stress through growth of new tissues that are better adapted to the stressful conditions, or die (intolerance to stress). Each of these modes can be differentiated based on specific components of the response function of stomatal conductance under decreasing moisture or dissolved oxygen.

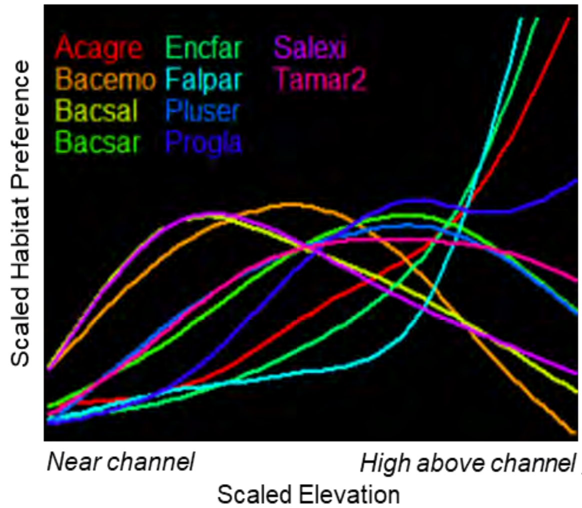
Experimental species

Experiment 1 will contain 12 woody plant species, including 10 that are common or dominant within different hydrological zones within the CRe, and 2 that are infrequent but desirable (Figure 5). These species vary both in the optimum and range of suitable habitat in terms of elevation above the channel. They also vary in a number of traits that are likely to result in tradeoffs in plant strategies with respect to both tolerance of, and acclimation to, drought and flooding (McCoy-Sulentic and others, 2017a).

Experiment 2 will only contain arrowweed, Emory's seepwillow, and Goodding's willow. These are the three species of immediate management interest.

Experimental design

We will use established techniques for manipulating soil water availability to induce drought and flooding stress on plants grown in containers, including both sustained and fluctuating conditions meant to simulate independent variation in base flows and daily fluctuating flows (Blackman and others, 2019; Gorla and others, 2015). Plants will be propagated in late winter of TWP years 1 and 2 by cuttings (most species) or seed when necessary (mesquite, acacia, creosote). Plants will be propagated in pure sand in containers at the NAU Research Greenhouse, then repotted to larger containers two weeks prior to initiation of experimental treatments to allow for root system expansion in response to those treatments.



Code	Common Name	Habitat Preference	Common CRe?
Acagre	Catclaw acacia	2-3	Y
Bacemo	Emory's seepwillow	1-2	Y
Bacsal	Mulefat	1-2	Y
Bacsar	Desert broom	2	Y
Encfar	Brittlebush	3	Y
Falpar	Apache plume	3	Y
Pluser	Arrowweed	2	Y
Progla	Honey mesquite	2-3	Y
Salexi	Coyote willow	1	Y
Tamar2	Salt cedar	1-3	Y
Popfre	Fremont cottonwood	1-2?	N
Salgoo	Goodding's willow	1-2?	N

*1 - Near channel, 2 - Intermediate, 3 - High above channel)

Figure 5. Variation in hydrological habitat preferences of 10 common woody riparian plants in the CRe. Models are based on repeat-monitoring data (Butterfield and others, 2018). Fremont cottonwood and Goodding's willow are not common enough in the system to develop models from observed data, but they are often used in restoration efforts within the CRe.

Experiment 1 (FY2021): Physiological thresholds

At the initiation of manipulative treatments, containerized plants will be placed on blocks of foam with known conductive properties in order to quantitatively control minimum soil moisture conditions and placed outside to create realistic vapor pressure deficit (atmospheric demand on stomatal conductance) conditions. These foam blocks will be placed within plastic bins, allowing for manipulation of the water table and hence water transport to the containers via capillary action. One individual of each species will be placed in each bin (12 plants per bin), creating a nested experimental design.

Bins will be subjected to one of three treatments: daily watering (control), consistent decline in soil moisture (dry-down treatment) or consistent increase in inundation (flooding treatment). Stomatal conductance, relative humidity, leaf turgor, soil water potential (dry-down treatment), and dissolved oxygen content of water (flooding treatment) will be monitored daily on a subset of replicates. These data will be used to quantify physiological thresholds to hydrological conditions that will allow us to predict species responses to environmental extremes, and to calibrate the subsequent experiment manipulating base flows and daily fluctuations. There will be 10 replicate bins per treatment for a total of 30 plants per species, and a total of 390 plants across the entire experiment. Similar experiments conducted by the Butterfield Lab at NAU have included on the order of 1000+ plants (e.g. Roybal and Butterfield, 2019), so this experiment will be well within their capacity.

Plants will be destructively harvested at the end of the experiment. Root systems will be scanned on a WinRhizo scanner to estimate total root length and surface area of absorptive roots. Cross sections of roots and basal stems will be scanned and analyzed for development of aerenchyma tissue. A subset of leaves will be scanned on a flatbed scanner to estimate total leaf area by multiplying specific leaf area by the total dry mass of all leaves. The volume of the stem will be estimated by the water displacement method after removal of phloem and pith in order to estimate stem tissue density. Total dry biomass of all three tissue types – roots, stems and leaves – will be quantified, as will total non-structural carbohydrates (energy reserves). Following recommendations from Tribal partners, plant material collected from along the Colorado River will be returned to the CRe after all data has been collected.

Generalized linear mixed models (GLMMs) will be used to test the hypothesis that species differ in their responses to drought and flooding, using log-response ratios (LRRs) of drought and flooding treatments relative to the control, and AICc for model selection. LRRs will be calculated for the maximum rate of decline in stomatal conductance, highest soil water potential or dissolved oxygen content at lowest stomatal conductance, value of minimum stomatal conductance, and stomatal conductance at the end of the experiment. These point measures capture critical aspects of the continuous response of stomatal conductance to experimental treatments (see Figure 4). The hypothesis that species differ in their drought and flood response strategies will be supported if the model with a species-by-treatment interaction term has greater support than a main effects model.

Associations between morphological adaptations (e.g. aerenchyma, leaf area-to-root area ratio) and physiological responses will be analyzed through multivariate analyses. After performing a dimensionality reduction on the morphological traits through an appropriate ordination method based on the data structure, the composite morphological variables derived from that ordination will be used as the constraining variables in an ordination of physiological response metrics. The results of this analysis will determine (1) the number of niche dimensions along which species differ in their hydrological adaptations, and (2) whether those species can be classified with respect to tolerance and acclimation strategies. These strategies will then be compared to field observations of species hydrological niches to assess potential constraints of different hydrological zones on viable functional strategies.

Experiment 2 (FY2022): Base flows vs. daily fluctuations

Only the three species of immediate management interest (Goodding's willow, arrowweed and Emory's seepwillow) will be included in this experiment, due to the increased number of experimental treatments. One individual of each species will be placed in each bin. Each bin will be assigned one of three average water table depths meant to simulate either the lower edge of the active channel, the transition between active channel and active floodplain, and upper edge of the active floodplain. Bins will then either receive a constant water table treatment, or a daily fluctuating flow treatment (Figure 6).

Contrasts between the constant and fluctuating flows simulating the same hydrological position will therefore receive the same amount of water on a daily basis, just differing in terms of the variability of that water table. Similar to Gorla and others (2015) and with support from Project K, water levels will be controlled by adjusting electronic valves connected to water inputs and outputs. The same daily measurements will be made as in Experiment 1 until stomatal conductance levels stabilize. There will be 10 replicates of each of the 6 treatment combinations, resulting in 60 bins and a total of 180 plants across all three species. Data will be analyzed using GLMMs used to test the hypothesis that fluctuating flows have effects on plant performance that are unique from average water levels alone. Model selection will be based on AICc.

Existing infrastructure at GCMRC and Butterfield Lab

Infrastructure from a pilot experiment on arrowweed, conducted in 2019 (Palmquist and others, *in prep*), will significantly defray operational costs of this project element. Materials include bins, pumps and hosing for regulating water levels and dissolved oxygen content.

Additional materials acquired through other funding sources are provided by equipment in the Butterfield Lab at NAU. This includes several porometers for measuring stomatal conductance, a combination pressure/cavitation chamber for quantifying water stress, time-domain reflectometer probes for quantifying soil water content, root scanner and associated software, refrigerators and freezers, balances and wet lab space, and in-house rates for plant tissue analysis at the NAU Histology Lab and NAU Research Greenhouse support.

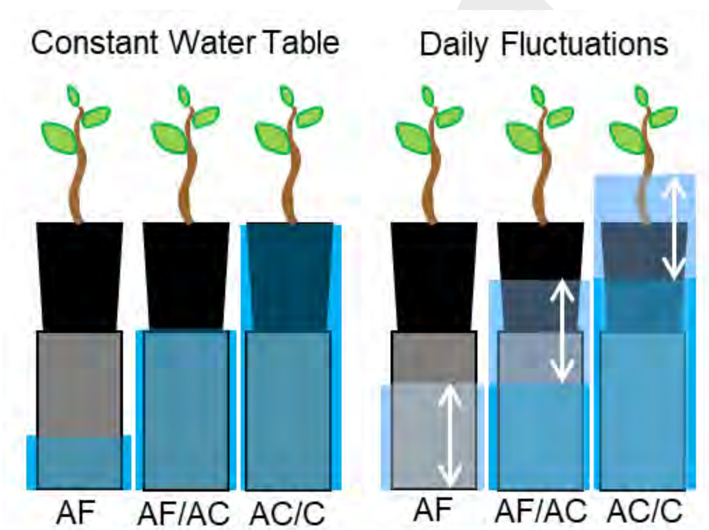


Figure 6. Experimental treatments meant to independently simulate base flows and daily fluctuating flows in: the Active Floodplain (AF), the zone inundated by HFEs but not by daily fluctuations; the interface between the Active Floodplain and Active Channel (AF/AC), where the Active Channel is the zone inundated by daily fluctuations; and the interface between the Active Channel and Channel (AF/AC), where the Channel is the zone below base flows.

Project Element C.3. Predictive Models and Synthesis

Brad Butterfield, Associate Research Professor, NAU, ECOSS
Emily Palmquist, Ecologist, USGS, GCMRC

This project element seeks to integrate data from Elements C.1 and C.2 with additional existing data sources to develop predictive models of LTEMP vegetation objectives under the influence of dam operations. To date we have relied on data from the monitoring program, which has led to new insights into the functional ecology (McCoy-Sulentic and others, 2017a; b) and hydrological and climatic sensitivity of CRe riparian vegetation (Butterfield and others, 2018; Palmquist and others, 2018a), as well as feedbacks on sedimentation (Butterfield and others, 2020). These data are limited to the observed range of variability in the CRe over the past 5-6 years, however, which constrains our ability to predict future changes in vegetation resource condition. The experiments elaborated in Element C.2 are one solution to this challenge, allowing us to separate effects of multiple aspects of dam operations on plant performance and test the extremes of species tolerances. A complementary solution is to take advantage of observations and experiments in regional river systems with similar species pools and climate. For example, arrowweed has been observed in recent years to be expanding into Virgin River riparian habitats previously occupied by tamarisk that have died from repeated beetle defoliations (González and others, 2020). Other literature reviews provide further predictions about responses of native plant diversity and secondary invasions by nonnative forbs into former tamarisk stands (González and others, 2017). These and other regional observations can help to inform predictive models of CRe vegetation change as beetle defoliation spreads in conjunction with the implementation of LTEMP experimental flows. At an even broader scale, biodiversity and hydrology databases can be leveraged to develop hydrological niche models based on species entire distributions, rather than being limited to individual research studies. These models help to predict interactive effects of climate change and dam operations on vegetation condition. As a first test of this method, we developed a new technique for quantifying interactions between riparian-dependence and climatic adaptations of willows (including coyote willow (*Salix exigua*), Goodding's willow and shining willow (*Salix laevigata*) all species present in the CRe) that can help to inform management actions across the western USA to promote species-specific willow habitat (Butterfield and others, *in press*). This study provided a proof of concept that we now propose to apply to a broader swath of CRe riparian plant species to better understand controls on their population health and growth.

Regional synthesis

We will synthesize existing data from the region through: 1) quantitative literature review, and 2) new analyses of monitoring databases from nearby river systems. The literature review will be structured to provide probability distributions of ecological responses to flow conditions, geomorphology and climate – both long-term average and punctuated events (e.g. drought, heat wave) – for explicit integration into the hierarchical Bayesian model used to generate vegetation condition predictions. We will build on existing literature reviews of rooting depths (Stromberg, 2013), species responses to hydrology and climate (McShane and others, 2015), tamarisk removal/mortality (González and others, 2017), and vegetation responses to environmental flows (Poff and Zimmerman, 2010; Shafroth and others, 2010). This quantitative review will follow a structured framework that facilitates integration of conceptual models into a hierarchical Bayesian modeling framework (Miller and others, 2013; Norris and others, 2012); see "Predictive models" below).

We will also analyze repeat monitoring data from other regional river systems to better understand and predict vegetation responses to flow and climate variables. We are developing a Memorandum of Understanding with NCPN and will look to develop additional relationships with other NPS monitoring networks. These data will be used to effectively extend the range of parameters beyond what are observed in the CRe to better predict the full range of potential vegetation responses to environmental variation through time.

Leveraging big data through informatics

There are massive nationwide and global databases that document where species occur, as well as hydrological and climatic datasets that can be merged in order to better understand the drivers of plant responses to flow regime. Given these opportunities, we have developed a workflow for determining species' hydrological and climatic niches using the National Hydrography Dataset Plus v.2 (NHDPlus). The novel workflow that we have developed in the R statistical and geospatial language extracts monthly average river flow and velocity data from NHDPlus associated with species occurrence records extracted from the Southwest Environmental Information Network. This is a novel integration and use of these existing datasets, so as a first step to assess the utility and validity of this approach, we have conducted an initial study of willow species hydrological and climatic niches (including two important CRe species, coyote willow and Goodding's willow. Willows were chosen for this initial analysis because they represent a diverse genus that has been well-documented in terms of where it occurs, and because many species are riparian obligate. Our initial results indicate that this method is quite valid, based on a strong concordance between the estimates of species hydrological niches, phylogenetic relationships and variation in their functional ecology (Figure 7; Butterfield and others, *in press*).

The next iteration of this modeling approach will be to develop range-wide models of common CRe riparian plant species to understand where the CRe lies within their broader realized hydrological and climate niches. These models will greatly improve our ability to predict species responses to ongoing climate change, as well as to alternative flow scenarios, in ways that are otherwise impossible based on the narrow range of environmental variability in our empirical CRe datasets.

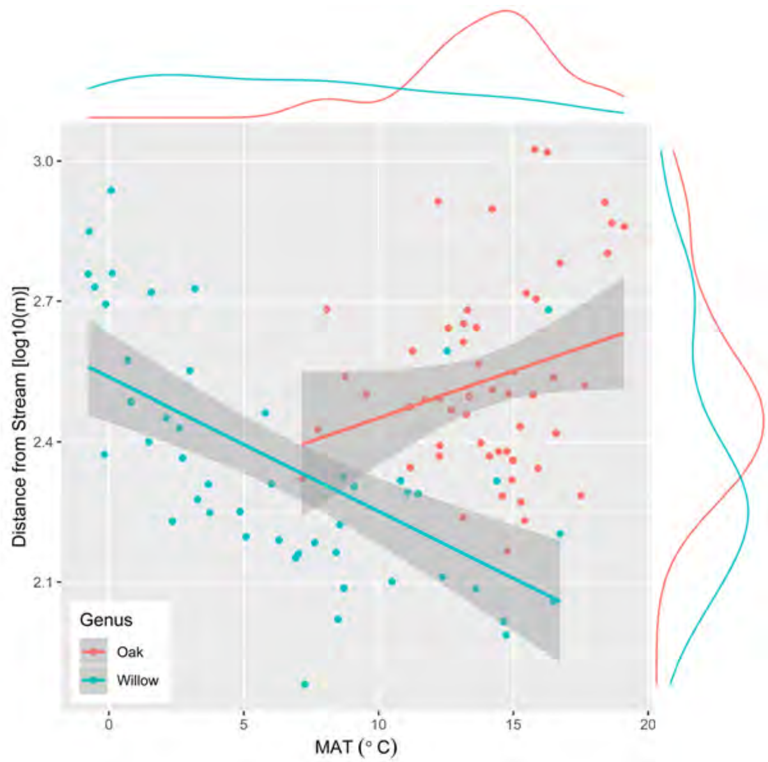


Figure 7. Example of results from new informatics workflow. Willows (48 species) exhibit distinctly different relationships between riparian-dependence and temperature niche than oak species (54) of the western USA. When combined with functional trait data, these results provide unique insights into how water supply and atmospheric demand shape the distributions of riparian trees. These patterns are based on >32,000 occurrence records of willows and oaks. MAT = mean annual temperature.

Predictive models: Structure and integration

We will develop a hierarchical Bayesian model of CRe vegetation that integrates each of the diverse types of data discussed above, as well as the vegetation maps produced via remote sensing (see Project L) and potentially data derived from repeat photos (see Project D.2) and vegetation treatments (Reclamation TWP C.7 and C.8), with outputs that directly address the LTEMP vegetation objectives. Example outputs conditioned on hydrological and climatic inputs will include vegetation-level characteristics such as total cover, % cover of different functional groups and native vs. nonnative species, as well as species-specific predictions for common species. Outputs will be assessed at a CRe-wide scale, as well as within floristically-distinct river segments and focal landforms/locations. In addition to peer-reviewed manuscripts that provide big-picture patterns as a function of current and future hydrology and climate, stakeholders and other interested parties will be able to manipulate model inputs through a Shiny R web application.

We will follow established frameworks for developing these models (Figure 8; Webb and others, 2014). The State-and-Transition model used in the LTEMP modeling process (Ralston and others, 2014), developed from historical datasets and expert knowledge, can be used as a starting point for the conceptual model (steps 1-2 in Figure 8) by providing initial expectations that will be updated through cycles of data integration and analysis.

This flexible modeling framework will facilitate multiple types of predictions, including but not limited to:

- Predicted changes in vegetation metrics under specific flow and climate conditions, from local to CRe-wide scales,
- Efficacy of specific vegetation management actions, and
- Flow conditions necessary to achieve specific LTEMP vegetation objectives.

In addition to the vegetation objectives specified in the LTEMP, we will work with stakeholders to identify other vegetation objectives and identify the conditions that could lead to those outcomes. This outreach is based on feedback received from stakeholders with a desire for greater involvement in vegetation resource management.

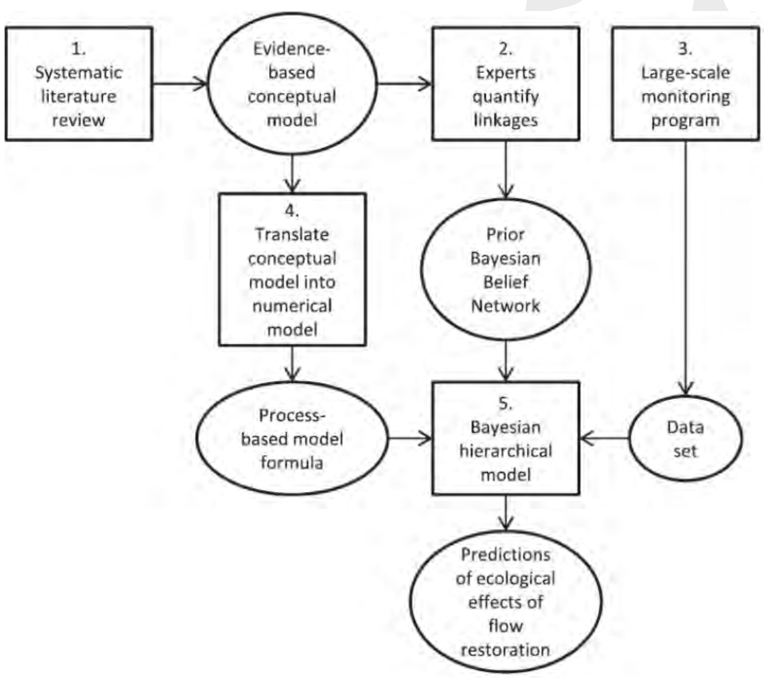


Figure 8. Example of a hierarchical Bayesian modeling framework (Webb and others, 2014). Box 3 depicted in this diagram will also include manipulative experiments, remotely-sensed vegetation maps and informatics-based models.

Project Element C.4. Vegetation Management Decision Support

Emily Palmquist, Ecologist, USGS, GCMRC
Brad Butterfield, Associate Research Professor, NAU, ECOSS

LTEMP non-flow experimental vegetation treatment includes revegetation efforts with native species, as well as vegetation removal to support recreational and sociocultural resources (see Reclamation TWP C.7 and C.8). Success of these efforts depends, in part, upon the hydrological and climatic settings in which they occur, due to strong linkages between hydrology, climate, and vegetation performance. Data products, analyses, and expertise generated in Project C related to these key factors in riparian plant survival can be leveraged to inform vegetation treatments. These vegetation treatment experiments are collaborative in nature and depend on coordination between NPS, the Tribes, and USGS. As outlined by LTEMP, this element includes personnel time to consult with and assist NPS and Tribal partners. Products and analyses from Elements 1-3 and the last Triennial Work Plan will be used to inform the design, implementation, and monitoring of treatments, as they are deemed useful to project partners.

As non-flow experimental vegetation treatments are developed and implemented, we will explore options for coordinated monitoring efforts of treatment sites among the monitoring listed in Element C.1., the assessment of vegetation removals on archaeologic sites in Element D.1, and NPS monitoring (Reclamation TWP C.7 and C.8). We will assist with developing plant monitoring protocols, as requested from project partners. We will also assess if site monitoring data collected by Element D.1 and project partners can be included in analyses and interpretations of the other Project C elements (C.1-3).

The species-specific niche models developed during the FY2018-20 TWP 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 can be compared to monitoring results from National Park Service and Tribal land managers in an iterative process to improve vegetation management outcomes. Focal species, useful models, and presentation of results will be determined based the needs and feedback of project partners.

Population genetic analyses of Goodding's willow, Fremont cottonwood (*Populus fremontii*), coyote willow and honey mesquite (*Prosopis glandulosa*) conducted during the FY2018-20 Triennial Work Plan will be provided to partners for the development of transfer zones appropriate for riparian plant species. For example, analyses indicate that in Fremont cottonwood there are distinct genetic groups associated with Marble Canyon, Grand Canyon, and any sites outside of the CRe. This information allows project partners to make informed decisions regarding the genetic make-up of restoration stock. Detailed explanations and interpretations of the results will be tailored to NPS and Tribal needs in discussions, in addition to a formal publication.

5.2. Outcomes and Products

Elements 1 through 3 are research and monitoring activities that individually and collectively answer research questions relevant to adaptive management in the CRe and vegetation responses to LTEMP flows. Element 4 provides decision support for ongoing experimental riparian vegetation treatments.

Project Element C.1.

- Monitoring data collected in FY2021 and FY2023 for random sampling and FY2021-22 for long-term monitoring sites, properly archived, and used in all other elements.
- Data summaries presented at GCMRC's Annual Reporting Meetings.
- Monitoring data made available online in collaboration with Project K.
- Journal publication regarding if and how flow patterns interact with other environmental variables to structure riparian vegetation in the CRe.

Project Element C.2.

- Presentations of results at GCMRC's Annual Reporting Meetings.
- Journal publication on the comparative physiological responses of 12 riparian species of interest to dry-down and flooding conditions.
- Journal publication on the differential impacts of fluctuating flows on Goodding's willow, arrowweed, and Emory's baccharis.

Project Element C.3.

- Presentations of results at GCMRC's Annual Reporting Meetings.
- Journal publication on possible riparian vegetation responses to future flows not yet experienced in the post-dam CRe.
- Journal publication on the hydrological and climate niches of common riparian species and where the CRe fits into those niches.

Project Element C.4.

- Participation in planning meetings with partners.
- Contributing data products, analyses, and expertise needed for planning and monitoring purposes.
- Assist with developing plant monitoring protocols, as needed.
- Assistance with native species plant material decisions and revegetation planning.

5.3. Personnel and Collaborations

Project C will collaborate with the GCDAMP Tribes in multiple ways. In addition to participating in GCDAMP organized meetings, we plan to maintain communication with Tribal representatives through several aspects of the work proposed here. In Element 1, we will continue to prioritize filling volunteer positions for riparian monitoring data collection with Tribal representatives. For example, the Navajo Natural Heritage Program botanist and staff from the Hualapai Department of Cultural Resources will continue to be contacted for suggestions on interested and qualified individuals. In Element 2, we plan to recruit students from GCDAMP Tribes to help with experiments through the NAU Research Experience for Undergraduates program. In Element 3, we will use our models to identify flow and climate conditions that would most likely support desired vegetation states identified by Tribal representatives, when and where possible. In Element 4, we plan to share all data products and interpretations related to LTEMP non-flow vegetation experiments with Tribal partners and provide interpretations tailored to their needs, as requested. We anticipate that any presentations of data products and interpretation will be interactive and a starting point for discussions about Tribal values and interests. Finally, we welcome discussions about how Project C can help Tribal stakeholders answer questions or reach goals regarding riparian vegetation at any time during this workplan.

The personnel supported by Project C include Emily Palmquist (full time), Bradley Butterfield (9-months annually, NAU cooperative agreement), one seasonal technician (6-months annually), and two NCPN botanists for one data collection trip per year (17 days, NPS cooperative agreement). Six contracted boat operators are hired for Grand Canyon data collection. Data collection for Element 1 requires 6 to 12 additional staff annually that are filled through collaborations and volunteers, so are not supported by the AMP. We work with Tribal representatives, GCNP, GLCA, and other stakeholders to fill these volunteer positions. Data collection and experiment management for Element 2 requires one to two additional staff that are filled through student positions at NAU and are not supported by the AMP. We anticipate recruiting a student from a regional Tribe to participate in the NAU Research Experience for Undergraduates program supported by the National Science Foundation. Additionally, this project utilizes data products and expertise in projects A.1, B.1, D.1, D.2, K.1, K.2, K.3, and L.1.

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7. Budget

Project C Riparian Vegetation Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
Fiscal Year 2021								
							14.00%	
C.1. Ground-based riparian vegetation monitoring	$65,898	$3,590	$1,650	$60,881	$8,500	$0	$18,738	**$159,256**
C.2. Plant experiments	$6,856	$0	$0	$0	$11,800	$0	$1,314	**$19,970**
C.3. Modeling riparian vegetation	$34,280	$0	$0	$0	$92,347	$0	$7,570	**$134,197**
C.4. Vegetation management support	$6,856	$0	$0	$0	$4,130	$0	$1,084	**$12,070**
Total Project C	**$113,890**	**$3,590**	**$1,650**	**$60,881**	**$116,777**	**$0**	**$28,705**	**$325,492**

Project C Riparian Vegetation Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
Fiscal Year 2022								
							22.00%	
C.1. Ground-based riparian vegetation monitoring	$75,625	$3,940	$1,565	$42,141	$8,500	$0	$27,375	**$159,146**
C.2. Plant experiments	$8,383	$0	$0	$0	$2,360	$0	$1,915	**$12,658**
C.3. Modeling riparian vegetation	$41,916	$0	$0	$0	$92,347	$0	$11,992	**$146,254**
C.4. Vegetation management support	$8,383	$0	$0	$0	$4,130	$0	$1,968	**$14,481**
Total Project C	**$134,307**	**$3,940**	**$1,565**	**$42,141**	**$107,337**	**$0**	**$43,250**	**$332,540**

Project C Riparian Vegetation Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
Fiscal Year 2023								
							28.00%	
C.1. Ground-based riparian vegetation monitoring	$76,710	$3,240	$3,310	$42,930	$8,500	$0	$35,588	**$170,278**
C.2. Plant experiments	$8,551	$0	$0	$0	$1,180	$0	$2,430	**$12,160**
C.3. Modeling riparian vegetation	$42,754	$0	$0	$0	$86,447	$0	$14,565	**$143,765**
C.4. Vegetation management support	$8,551	$0	$0	$0	$4,130	$0	$2,518	**$15,199**
Total Project C	**$136,566**	**$3,240**	**$3,310**	**$42,930**	**$100,257**	**$0**	**$55,100**	**$341,403**

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

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

In order to reduce the Project C overall budget and in response to stakeholder comments regarding reducing the frequency of monitoring in GCMRC, the two monitoring trips per year were reduced to one monitoring trip per year in FY2022 and FY2023. In the years that we collect data for the random samples, we can provide an assessment of the riparian vegetation as whole. For the years we collect long-term monitoring sandbar/campsite data, we can provide an assessment of the state of vegetation at recreationally important sites. Not collecting a full dataset each year means we will have limited abilities to link changes in riparian vegetation to LTEMP experimental flows, particularly if those flows are conducted during years we do not sample.

These sampling trips were cut over other aspects of Project C for a few reasons. First, the cost of the other three elements is mostly staff time, so cuts to those elements would not have noticeably reduced our budget. Secondly, if we cut staff instead of data collection, we would not be able to enter, manage, and analyze the data that were collected. Thirdly, the experiments in Element 2 were reduced (see below), but are the primary way we can tie dam operations to riparian plant success or failure. The other two elements entirely fund staff time to analyze and interpret existing data (Element 3) and assist with LTEMP non-flow vegetation experiments (Element 4).

Part of Project Element C.2. Determining Hydrological Tolerances and Management Tools for Plant Species of Interest

The scope and extent of experimental manipulations of riparian plant hydrological tolerances were reduced. The reductions to this project consist of fewer questions being tested and lower sample sizes. We removed a sand burial experiment, in which arrowweed would be cut and buried with sand, to simulate the LTEMP non-flow experimental treatments. We also cut non-structural carbohydrate analyses, which would provide data on plant stress, health, and survival mechanisms. Finally, we cut a complementary experiment using carbon isotopes to explore differences in water sources among species. After acquiring necessary infrastructure in FY2021, FY2022 and FY2023 costs are for plant propagation and maintenance. The cost of these experiments was already low, due to a cooperative agreement with Dr. Butterfield at NAU and contributed resources from the Butterfield Lab. In-house rates are 50% of the external rates for NAU services.

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

1. Investigators

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2. Project Summary and Purpose

The construction and subsequent 50+ years of operation of Glen Canyon Dam (GCD) has profoundly altered the downstream aquatic and terrestrial ecosystem of the Colorado River corridor in lower Glen Canyon, Marble Canyon, and Grand Canyon. Among many effects, dam construction and operation have affected geomorphic processes responsible for the formation and preservation of the Holocene age, fluvially-derived sediment deposits in which numerous archaeological sites and other resources of cultural importance are embedded. The affected archaeological resources are valued not only for their information potential to archaeologists, but also as the homes and resting places of the ancestors of several Native American Tribes who reside in the region today. They are also valued as tangible records of indigenous peoples' tenure in this landscape.

Other resources of cultural value in the Colorado River ecosystem (CRe) include the plants that grow on the Holocene deposits, the birds that nest in the vegetation, the reptiles and mammals that inhabit the riparian zone, as well as the myriad kinds of aquatic life that live in the river. This project focuses specifically on studying and documenting the dam's effects to the terrestrial riparian environment of the CRe and its associated archaeological resources, while recognizing the linkages this work has for other culturally valued resources as well.

During the past three decades, researchers affiliated with the U.S. Geological Survey (USGS) and various academic institutions have monitored and researched GCD effects on cultural resources in the CRe, including specifically the dam's physical effects on archaeological sites. While it is recognized and acknowledged that the dam and its operation are not the only sources of change affecting the CRe and associated archaeological sites, this project focuses on researching and monitoring dam effects, in keeping with the mandates of the Grand Canyon Protection Act (GCPA). Furthermore, while it is also recognized and acknowledged that Native American Tribes affiliated with Grand Canyon view the effects of dam operations as being broader than just physical impacts to the ecosystem, and they believe that dam effects can potentially include impacts to traditional spiritual values as well as indigenous societies more generally, this project focuses on impacts which are amenable to investigation by scientific methods, with the understanding that those impacts which are not amenable to scientific investigation are best identified and addressed by the specifically-affected cultures at risk.

From a physical perspective, GCD has reduced downstream sediment supply to the Colorado River by about 95% in the reach upstream of the Little Colorado River confluence and by about 85% downstream of the confluence (Topping and others, 2000). Operation of the dam for hydropower generation has additionally altered the flow regime of the river in Grand Canyon, largely eliminating pre-dam low flows (i.e., below 5,000 ft^3/s) that historically exposed large areas of bare sand (U.S. Department of the Interior, 2016a; Kasprak and others, 2018). At the same time, the combination of elevated low flows coupled with the elimination of large, regularly-occurring spring floods in excess of 70,000 ft^3/s has led to widespread riparian vegetation encroachment along the river, further reducing the extent of bare sand (U.S. Department of the Interior, 2016a; Sankey and others, 2015). Kasprak and others (2018) report that the areal coverage of bare sand has decreased by 45% since 1963 due to vegetation expansion and inundation by river flows. Kasprak and others (2018) forecast that the areal coverage of bare sand in the river corridor will decrease an additional 12% by 2036.

The changes in the flow regime, reductions in river sediment supply and bare sand, and the proliferation of riparian vegetation have affected the condition and physical integrity of archaeological sites and resulted in erosion of the upland landscape surface by reducing the transfer (termed "connectivity") of sediment from the active river channel (e.g., sandbars) to terraces and other river sediment deposits in the adjoining landscape (U.S. Department of Interior, 2016a; Draut and Rubin, 2006, 2008; Draut and others, 2008, 2010; Draut, 2012; East and others, 2016, 2017; Kasprak and others, 2018; Sankey and others, 2018a, b; Cook and others, 2019). Many archaeological sites and other evidence of past human activity are now subject to accelerated degradation due to reductions in sediment connectivity under current dam operations and riparian vegetation expansion which are tied to regulated flow regimes (U.S. Department of the Interior, 2016a; East and others, 2016, 2017; Cook and others, 2019).

The GCD Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) predicts that conditions for achieving the goal of preservation for archaeological resources, termed "preservation in place," will be enhanced as a result of implementing the selected alternative (U.S. Department of Interior, 2016a). High-Flow Experiments (HFEs) are one component of the selected alternative that will be used to resupply sediment to sandbars in Marble and Grand Canyons, which in conjunction with targeted vegetation removal, is expected to resupply more sediment via wind transport to archaeological sites, depending on site-specific riparian vegetation and geomorphic conditions. However, HFEs have been shown to directly erode terraces that contain archaeological sites in Glen Canyon National Recreation Area (GLCA; East and others, 2016; U.S. Department of Interior, 2016a).

HFEs have also been shown by Sankey and others (2018b) to rebuild or maintain sandbars that provide sand to resupply aeolian dunefields containing archaeological sites throughout Marble and Grand canyons. Aeolian dunefields were resupplied with sand at deposition of rates of 2-8 cm per year from HFE deposits in half of the flood-site instances monitored after the 2012, 2013, 2014, and 2016 HFEs (Sankey and others, 2018b). Sankey and others (2018b) also found evidence for cumulative increases in sediment resupply of dunefields when annual HFEs are conducted consistently in consecutive years.

This project addresses the effects of dam operations on fluvially-derived sedimentary deposits and associated cultural resources through four project elements:

- **Element D.1** quantifies the geomorphic effects of ongoing and experimental dam operations and riparian vegetation management, focusing on effects of HFEs on the supply of sediment to cultural sites. The dam operations and vegetation management of interest are those undertaken by the LTEMP Record of Decision (ROD; U.S. Department of the Interior, 2016b) through 2036. The data and analyses from this project will allow the GCDAMP to objectively evaluate whether and how these flow and non-flow actions directly affect cultural resources, vegetation, and sediment dynamics. It will also allow determination of how flow and non-flow actions will ultimately affect the long-term preservation of cultural resources and other culturally valued and ecologically important landscape elements located within the river corridor downstream of GCD.

- **Element D.2** uses repeat photography methods and an analysis of matched images to document changes in riparian cover at locations throughout the CRe. The purpose of documenting these changes is to refine our current understanding of how vegetation growth and expansion has evolved and affected the availability of open sand sources and related consequences for cultural resource preservation throughout the CRe.

- **Element D.3** will assemble and summarize the previous three decades of cultural resource-related research and monitoring which forms the foundation for this project and informs other cultural resource National Historic Preservation Act (NHPA) compliance activities being undertaken in the CRe under the guidance of Reclamation's recently completed Historic Preservation Plan for cultural resources (Bureau of Reclamation, 2018).

- **In Element D.4 (not funded),** GCMRC staff offer to provide science support to the proposed excavation, study and interpretation of an eroding archaeological site (AZ C:13:339) that is targeted for excavation in the near future by a consortium of Tribal, academic, and National Park Service (NPS) archaeologists. Specifically, the geomorphic, geoarchaeological, and lidar remote sensing expertise currently existing within GCMRC will be made available to assist with documenting the processes responsible for the formation and subsequent modification of the site and surrounding river corridor landscape. This project element is intended to complement and enhance cross-cultural communication and collaboration among a variety of diverse Tribal and scientific perspectives represented by current stakeholders and scientists engaged in the GCDAMP.

3. Hypotheses and Science Questions

Project Element D.1.

Research Questions:

- Do HFEs increase the resupply of river sand to archaeological sites in the river corridor and offset erosion, thus achieving the LTEMP resource goal of preservation in place?
- Does removal of riparian vegetation located between HFE-sediment supplied sand bars and archaeologic sites increase the probability of preservation in place and thus achieving the LTEMP resource goal?
- Do vegetation and biological soil crust cover within archaeological sites that are not resupplied with sediment from HFEs help to reduce erosion and increase the probability of achieving the LTEMP resource goal of preservation in place?

Hypothesis:

- Sediment transfer at the experiment sites is greater under the combined effects of vegetation removal followed by an annual HFE.

Project Element D.2.

Research Questions:

- How has riparian vegetation encroachment since dam closure affected the availability of open sand source areas that formerly served to cover and protect archaeological sites in the CRe?
- Does pre-dam riparian vegetation cover within the old high-water zone vary through time? Specifically, do historical photos taken during drought periods characterized by lower annual flows show more riparian cover compared with photographs taken during periods characterized by wetter conditions and higher annual flows?

- How has the composition and density of riparian vegetation cover changed during the 50+ years since dam closure?
- Are patterns of vegetation encroachment evident in the historical photo record, and if so, are they indicative of natural successional processes or are they more reflective of changes in dam-controlled flow regimes?

Hypotheses:

- Hypothesis 1: Riparian vegetation composition and density in the CRe has varied through time in response to differences in both pre-dam and post-dam flow regimes. These variations have affected the amount of open sand area serving as sources of sediment at archaeological sites.
- Hypothesis 2: Patterns of riparian vegetation encroachment in the post-dam period have varied through time in response to dam-controlled flow regimes. The current flow regime is significantly reducing open sand areas below the 25,000 ft^3/s flow line compared to pre-Modified Low Fluctuating Flows (MLFF).

Project Element D.3.

Research Questions:

- How has the previous three decades of research and monitoring informed current preservation strategies and NHPA compliance activities in the CRe?
- How have multi-cultural perspectives informed development of the cultural program of the GCDAMP since its inception 25 years ago?
- What lessons have been learned from the successes and failures of the previous 30 years of research, monitoring, and NHPA compliance-related activities in the GCDAMP cultural program that can help improve the effectiveness of cultural resource management actions in the next 30 years?

Project Element D. 4. (not funded)

Research Questions:

- What do the sub-surface deposits at and near site AZ C:13:339 reveal about the river corridor's physical and biological environment, past climate, and human manipulation of the environment before, during and following occupations at this location?
- How have past and present river flows, debris flows, overland flow, and other geomorphic processes affected the preservation and current condition of cultural deposits at site AZ C:13:3339?

- How have recreation-related activities, including hiking and camping along the Beamer trail, affected the geomorphology, as well as surface and sub-surface archaeological features and cultural deposits, at site AZ C:13:339?

4. Background

Significance and Justification

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 CRe's 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 LTEMP ROD (U.S. Department of Interior, 2016b), 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 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 Element D.1 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 Element D.1 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 GCPA (U.S. Department of Interior, 1992) 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 NHPA (U.S. Congress, 1966) has somewhat similar obligations as GCPA (Bureau of Reclamation, 2017).

To fulfill its compliance obligations under the NHPA, Reclamation has developed a Programmatic Agreement (PA; Bureau of Reclamation, 2017) and a Historic Preservation Plan (HPP; Bureau of Reclamation, 2018). 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.

Science

More than two decades of research and monitoring in the CRe have demonstrated that throughout Grand Canyon, numerous archaeological site and other cultural resources are subject to degradation from erosion processes and visitor impacts (U.S. Department of the Interior, 2016a; Cook and others, 2019). Many of these sites occur in landforms, such as terraces, debris fans, and dunefields that are located above the elevations inundated by the contemporary river channel, yet research and monitoring have demonstrated that the effects of dam operations have nonetheless accelerated and exacerbated rates of erosion affecting many of these sites (U.S. Department of the Interior, 2016a; East and others, 2016; 2017).

Research has shown that landforms containing cultural resource sites have become disconnected (i.e., no longer receive sediment) from the active river channel downstream of the dam due to the combination of reduced sediment supply in the river, riparian vegetation encroachment, and alterations in flow, which historically supplied sediment (e.g., during floods) but also exposed that sediment for transport (e.g., by wind during low flows; East and others, 2016; Kasprak and others, 2018; Sankey and others, 2018a).

Terraces and other Holocene fluvial sediment deposits are a substantial component of sediment resources in the ecosystem. They additionally contain widespread evidence of past human activity (e.g., archaeological sites; Fairley and others, 1996; Hereford and others, 1996; U.S. Department of the Interior, 2016a). Thus, the ongoing loss of these sediment deposits is contributing to the loss of all sediment-dependent resources in the CRe, including cultural sites (U.S. Department of the Interior, 2016a; Collins and others, 2016).

In some places, for example at the large terraces in the Glen Canyon reach of the Colorado River, sediment transfer between the active river channel and upland areas occurs primarily through fluvial erosion and mass failure processes (East and others, 2017). In these areas HFEs have resulted in the erosion of terraces, mainly from the change in pore pressure gradient after flood water recession exposes saturated terrace banks, which then shed material into the river channel (U.S. Department of the Interior, 2016a; Grams and others, 2007). In other areas, sediment connectivity results from aeolian transport of sand from sandbars to dunefields located on terraces or debris fans (U.S. Department of the Interior, 2016a; East and others, 2016; Draut, 2012; Sankey and others, 2018a, b). In both situations, the deposition or erosion of sediment can have direct impacts on buried or exposed archaeological sites situated on these surfaces, and can also have indirect impacts such as offsetting rates of erosion from natural processes in the surrounding landscape (U.S. Department of the Interior, 2016a; Collins and others, 2016; Sankey and Draut, 2014; Sankey and others, 2018b). These impacts are in turn interpreted by NPS and Tribal resource managers as being either beneficial or deleterious to the cultural resources in question.

The LTEMP (U.S. Department of Interior, 2016a) relied on a series of conceptual and numerical models to evaluate the likely responses of resources to a suite of proposed alternatives for operating GCD through 2036. The models incorporated past scientific learning and produced generalized predictions about how resource conditions would potentially change under each alternative. The model-based analyses predicted that the alternative selected for implementation in the LTEMP ROD (U.S. Department of the Interior, 2016b) would result in modest benefits for cultural resources by improving sediment conditions that help to stabilize and preserve archaeological sites *in situ*, while also benefiting natural processes, campsites, riparian vegetation, hydropower, endangered fish, and other resources valued by society.

Over the past decade, GCMRC scientists have developed and refined methods for tracking trends and quantifying rates, amounts, and sources of geomorphic change affecting cultural resources in the CRe (Kasprak and others, 2017; Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016, 2017; Sankey and others, 2018a, b). These methods are perfectly suited to evaluating whether the predictions of resource improvement in the LTEMP occur during the next two decades (U.S. Department of Interior, 2016a, b). Specifically, the methods can be used to evaluate whether changes in operations improve sediment supply to archaeological sites and the associated landforms in which these sites are embedded, and whether such changes in turn result in a reduction of erosion rates and improved preservation of the physical attributes that are necessary to maintain site integrity under the NHPA.

The LTEMP EIS (U.S. Department of the Interior, 2016a) identifies river terraces, specifically in the GLCA reach, as being vulnerable to erosion and degradation from HFEs which are otherwise intended to distribute sediment throughout the Colorado River downstream of the Paria River (see also Grams and others, 2007).

DOI agencies and Tribal resource managers have identified a need for quantifying the effects of dam operations on the erosion of terraces and other river sediment deposits in Glen, Marble, and Grand canyons by determining erosion rates during the approximately two decades since the implementation of the previous ROD (U.S. Department of Interior, 1996) with a river flow regime of episodic controlled floods and restricted hydropeaking (U.S. Department of the Interior, 2016b).

The LTEMP ROD (U.S. Department of the Interior, 2016b, subsection 6.4.) also identifies vegetation management as a non-flow action to assist with cultural site protection. Accordingly, the NPS is working with Tribal partners and GCMRC to remove woody riparian vegetation at individual sandbars in order to increase campsite area and also to increase the amount of river sand that is transported by wind and deposited on adjacent dunefields and archaeological sites. GCMRC's ongoing program for monitoring the effects of dam operations on the geomorphic condition of archaeological sites, which was implemented in Project 4 of the FY2015-17 work plan and Project D of the FY2018-2020 Triennial Work Plan (TWP), is well-suited for monitoring the vegetation removal experiments and for quantifying the effectiveness of the treatments.

5. Proposed Work

Project Elements

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

Joel B. Sankey, Research Geologist, USGS, GCMRC
Helen Fairley, Archaeologist/Social Scientist, USGS, GCMRC

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 HFEs increases the resupply of river sand to archaeological sites in the river corridor and offsets erosion, thus achieving the GCPA goal of resource improvement and the LTEMP and NHPA resource goals 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 GCPA, NHPA, and LTEMP resource goals.

- Determining if vegetation and biological soil crust cover within archaeological sites that are not resupplied with sediment from HFEs help to reduce erosion and increase the probability of achieving the LTEMP resource goal of preservation in place.

There are more than 350 river corridor archaeological sites in Grand Canyon (Fairley and others, 1996; East and others, 2016). Most sites are located in river sand deposits reworked by water, wind, and gravity (Fairley and others, 1994; Pederson and O'Brien, 2014; East and others, 2016). Most sites are eroding, and many are degraded specifically owing to gully erosion (Damp and others, 2007; East and others, 2016, 2017). However, river sand can help provide a protective cover to preserve sites in place (Collins and others, 2016; East and others, 2016, 2017).

Thus, the geomorphic condition of sites is affected by how Colorado River sand is transferred among landforms in Grand Canyon (Draut and others, 2012; Collins and others, 2016; East and others, 2016, 2017; Kasprak and others, 2017; Sankey and Draut, 2014; Sankey and others, 2018a, b). The transfer of river sand from sandbar deposits to archaeological sites often occurs by wind in this ecosystem (Draut and others, 2012; Collins and others, 2016; East and others, 2016; Sankey and others, 2018a, b), although in the pre-dam era, annual spring floods were responsible for redistributing large volumes of sediment to river corridor sites. With the elimination of spring floods and all flows higher than 45,000 ft^3/s, wind transport is now the main process for redistributing sediment from the river channel to archaeological sites.

We use repeat ground-based light detection and ranging (lidar) surveys to measure changes in geomorphic condition of archaeological sites (Kasprak and others, 2017; Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016, 2017; Sankey and others, 2018a, b). We select sites for lidar measurements from the entire population of river corridor sites using two site classification systems (East and others, 2016; 2017) 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 FY2018-20 TWP, assuming fieldwork is allowed to take place in FY2020, the sample size of sites where lidar surveys have been conducted will be 30 sites (Caster and others, *in review*). During the FY2021-23 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. These monitoring data will also be leveraged, as described below, to evaluate vegetation management implemented by NPS under the LTEMP.

In 2019, the NPS implemented experimental vegetation removal treatments on sandbars adjacent to five archaeological sites. The treatments were intended to increase the supply of sand from the sandbars to the archaeological sites.

In 2020, the NPS will conduct maintenance at the sandbars to remove any vegetation regrowth and will conduct vegetation removal at one more sandbar to bring the total number of treated sites to six. The NPS will revisit the sites to remove any vegetation regrowth in each year of the FY2021-23 TWP.

In this project, in addition to monitoring the geomorphic condition of archaeological sites, we will quantitatively evaluate the outcome and effectiveness of those vegetation management treatments. Lidar surveys acquired before and after the vegetation removal treatments, and after each annual site maintenance visit by the NPS, provide datasets for geomorphic change detection (Kasprak and others, 2017; Sankey and others, 2018b; Caster and others, *in review*) from which we will determine whether sediment transfer occurs and increases at the sites as a function of the vegetation removals. In addition to quantifying sediment transfer, we will use the lidar surveys and field observations, as well as remote monitoring cameras that exist at some of the sites, to quantify the vegetation that is removed and regrows during each year of the experiment. Figure 1 shows examples of photos and lidar data acquired before and after the removal of vegetation in 2019 at one of these sites.

We will evaluate the effects of vegetation removal for sediment transfer in several ways at the experiment sites. At many of the sites, multiple years of lidar surveys exist during the decade preceding the vegetation removal treatments. Thus, we can use those data to evaluate sediment transfer before and after the vegetation treatments, including years during which HFEs were and were not conducted. As described above, we also have comparable lidar survey datasets for a sample of 30 sites which we can use as experimental controls to measure sediment transfer at sites where vegetation has not been removed. 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 that may be conducted in 2020-2022 will provide insight concerning effects of vegetation removal followed by an annual HFE. In FY2023, the last year of this TWP, we plan to report on the outcome of the experiment, and effectiveness of the vegetation removal treatments implemented through FY2022.

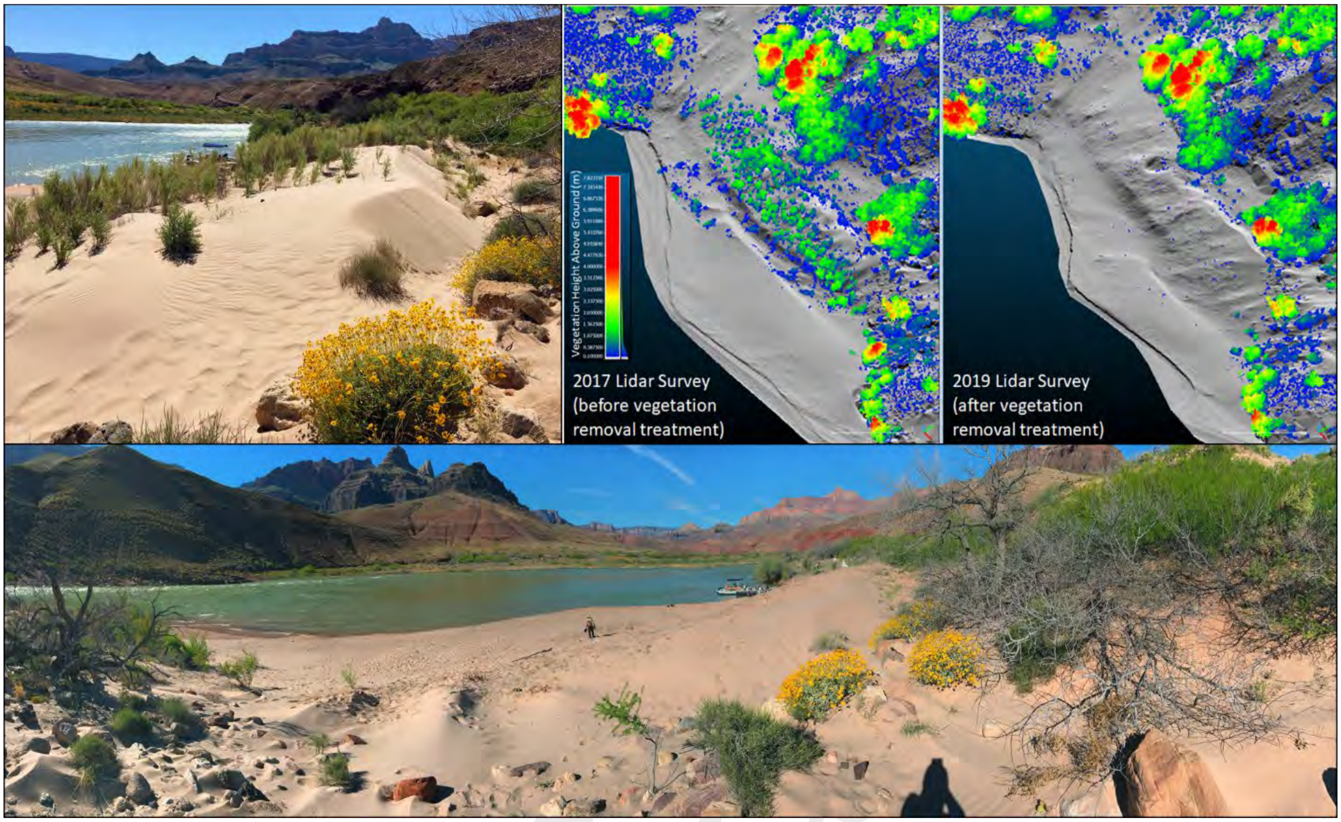

Figure 1. Photos illustrating vegetation removal implemented at one of the sites by NPS in 2019, and examples of lidar data that will be used to evaluate treatment effects. Top left panel shows the sandbar and dune immediately prior to vegetation removal in April 2019. Bottom panel shows the sandbar, dune, and surrounding landscape immediately after the vegetation removal in April 2019. Top middle and right panels show lidar-derived digital elevation models (DEM; gray surface) and vegetation canopy height models (CHM; blue-green-red surface) acquired before and after the vegetation removal.

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

Helen Fairley, Archaeologist/Social Scientist, USGS, GCMRC

Repeat photography provides a cost-effective method for documenting landscape-scale changes. Analysis of matched images can help to inform our current understanding of how dam operations have altered the physical and biological conditions contributing to the preservation and degradation of cultural resources in the CRe. Since FY2016, GCMRC staff and volunteers have been collecting precise matches of historical images taken primarily during the 1923 USGS Birdseye expedition. The initial results of this pilot photo matching effort have proven to be highly informative and useful for a variety of GCMRC projects including Projects C and D in the FY2018-20 workplan (Sankey and others, 2018a; SBSC website). Not only do the matched images visually document and illustrate some of the dramatic changes in the environment that have taken place since closure of the dam, in some cases they also provide a detailed record of post-dam changes in river corridor vegetation.

Additionally, they provide a record of changes to the formerly unvegetated 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.

Up until now, GCMRC has relied heavily on volunteer labor to acquire high quality photo matches, focusing primarily on panoramic images of the riparian zone taken during the 1923 Birdseye expedition. In addition, some rematches of the 1889-1890 Stanton expedition photographs have been acquired. 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 (Webb, 1996), and the Stanton photographs were re-matched a second time in 2010-2011 (Webb and others, 2011; Scott and others, 2018). The most 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, GCMRC scientists and volunteers collected information on species-level vegetation changes at each of the approximately 200 locations throughout the river corridor with recently matched views; however, because the project was not funded in the FY2018-20 TWP, and we had 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.

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 unique comparison of pre-dam riparian vegetation conditions closer to the time of dam construction and under somewhat different flow conditions as compared to the photographs taken 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. If there is interest from Tribes, we will also organize one or more workshops to discuss initial outcomes from the first phase of this project, solicit Tribal perspectives on the interpretation of these results and discuss how photographic matches can be used to inform Tribal monitoring programs or enhance other components of the AMP. We can also use the workshop as a platform for providing technical training in the application of this method for environmental change monitoring, if desired. To minimize costs, these workshops will be scheduled in conjunction with other planned AMP meetings or will occur at individual Tribal headquarters.

Schedule:

- FY2021: We propose to focus one staff member part-time on analyzing and writing up the results of the past several years of photo-matching work. A draft manuscript will be produced. We also propose to begin matching photographs from the Goldwater and Borden collections.
- FY2022: A workshop will be organized to disseminate initial results and solicit Tribal feedback on cultural or biological interpretations of these initial results. We will complete review and publication of the Birdseye photo-matching project. We will continue to match photographs from the Goldwater and Borden collections.
- FY2023: We will continue to match photographs from the Goldwater and Borden collections. A journal article on the Goldwater matches will be produced. Photo matches will be made available to the public via GCMRC's website.

Project Element D.3. Cultural Program History

Helen Fairley, Archaeologist/Social Scientist, USGS, GCMRC

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 1996 ROD for modifying operations of Glen Canyon Dam. Throughout the ensuing decades, representatives and scientists from the USGS, Bureau of Reclamation, NPS, and six traditionally affiliated Tribes have produced numerous studies and reams of data, much of which is buried in agency files or in grey literature reports and is largely inaccessible to AMP stakeholders as well as the general public. The purpose of the NHPA is not only to protect and preserve historic and prehistoric sites, buildings, landscapes, and objects, it is also intended to ensure that the public benefits from the protection of these resources through sharing knowledge that is gained as a result of activities undertaken in support of NHPA. Thus, federal agencies have an obligation to provide access to information gained through compliance with NHPA, as long as it does not cause harm to the historic properties that the law is designed to protect.

In fulfillment of the NHPA mandate to make knowledge gained from the past 30 years of federally-funded research and monitoring accessible to the public, to educate new and future members of the GCDAMP about the past activities and learning achieved by the GCDAMP cultural program, and to preserve the memories and knowledge of individual members of the cultural program before it is too late to recover them, we propose to assemble a comprehensive history of the GCDAMP cultural resources monitoring and research programs. The focus will be on documenting cultural program activities conducted since 1995 and funded by the GCDAMP to study, protect, and enhance public education about Tribal, archaeological, geo-archaeological, and cultural landscape resources in the CRe, including their connections to other parts of the GCDAMP program.

Along with other stakeholders in the GCDAMP, the signatories to Reclamation's Programmatic Agreement for Cultural Resources and researchers involved in studying and monitoring cultural resources in the CRe 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 inaccessible in agency files, no longer remembered, or are unknown to newer members of the GCDAMP. After 30+ years of involvement in the GCDAMP, several key individuals involved in the program are approaching or actively contemplating retirement. It would be beneficial to the GCDAMP and the public to record their personal knowledge of the program before it is lost to collective memory.

As part of the previous FY2018-20 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 intended, nor was it written in a manner suitable, for publication as a public report. This project will draw upon some of this previously assembled information, but it will incorporate considerable additional historical documentation to capture the "who, when, what and why" components of the program. This project 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. Personal recollections will be substantiated by documentary evidence, including primary source materials in agency files, to the maximum extent possible.

It will place the various projects and products of the GCDAMP cultural program in historical context so that members of the public and future AMP stakeholders not only can understand what was done when and by whom, but also importantly, why.

The intent is to compile a detailed summary of previous cultural program research and monitoring within a historical context. The final product will take the form of a traditional administrative history document, with historical times lines and themes; however, oral history interviews, key primary documents, and other supporting materials will be made available through a supplementary web platform.

This project will enhance and complement but will not duplicate the GCDAMP administrative history project that is currently under development through a contract with Arizona State University. The ASU administrative history currently contains very little information relating to the cultural aspects of the GCDAMP aside from several oral history interviews; however, some of the interviews currently available on the ASU website provide primary source material that will help to inform project D.3. The final published document will serve as a useful reference for federal agencies and GCDAMP stakeholders, especially new federal employees and stakeholders who join the program in future years; it will also serve the broader interests of the American public.

Schedule:

- FY2021: Consult with cultural program participants, PA signatories, AMP stakeholders and other interested parties to identify high priority topics for inclusion in the final report; interview key cultural program participants; draft a preliminary report for initial review.
- FY2022: Incorporate review comments; prepare final draft for final review and publication. Post report and supplementary documentation on ASU's administrative history website, AMP wiki, and/or other publicly accessible website (TBD).

Project Element D.4. Geomorphic Research in Support of NHPA Compliance Activities (not funded)

Helen Fairley, Archaeologist/Social Scientist, USGS, GCMRC
Joel B. Sankey, Research Geologist. USGS, GCMRC

In FY2021-23, the Pueblo of Zuni and Grand Canyon National Park are proposing to undertake a partial excavation of an eroding archaeological site, located in the Colorado River corridor in eastern Grand Canyon. This site is eroding due a variety of processes including overland flow, creep, camper and hiker impacts associated with the Beamer Trail, and indirect effects from the operation of Glen Canyon Dam.

One goal of this proposed excavation project, in addition to salvaging information that will be otherwise lost to ongoing erosion of the site, is to pilot a demonstration project of a collaboratively-designed archaeological research program that integrates the perspectives of Tribal members with those of western scientists.

While the focus of the proposed collaborative excavation project is on recovering information from two eroding prehistoric cultural features, this excavation project offers a rare opportunity to examine and extract information from the sedimentary matrix in which these features, and the site as a whole, are embedded. A detailed examination of the sedimentary and geomorphic context of the site can enhance current understanding of the geomorphic processes and physical and biological conditions responsible for shaping this part of the CRe. Therefore, Project Element D.4 is proposed as way to complement and enhance the archaeological excavation project through providing science support to the project focused on recovering and interpreting information from the sedimentary and geomorphic-landscape context of the site. The information gained from this study will help to inform the archaeological and indigenous interpretations of the site by contributing information related to the site's original formation, subsequent preservation, and recent degradation, as well as information on prehistoric climatic conditions, the prehistoric environmental setting, and possibly also prehistoric human manipulation of the local environment.

In Project Element D.4, GCMRC proposes to provide science support to the archaeological mitigation project by contributing geoarchaeological, geomorphological, and lidar remote sensing expertise to the culturally-focused archaeological research effort. We have identified several research questions in this work plan that this project element would address; these questions may be refined, and other questions may be developed through future consultation with the participating Tribes and NPS. Information that addresses these research questions will be acquired and compiled through applying standard scientific sedimentological and geomorphic analyses and three dimensional mapping (e.g., lidar, photogrammetry, topographic surveying) techniques, as well as through methods and approaches developed in consultation with traditional indigenous farmers, Zuni soil conservation experts, and other Tribal members who have practical hands-on knowledge about sediment and soils from having worked extensively with these materials.

If for some reason the proposed excavation project is unable to proceed in FY2021-23, most of the work described in this project element can still be completed, with minor modifications, to provide a foundation of geomorphic and stratigraphic information that would inform future mitigation work at this site. Ideally, however, this work will be conducted in close collaboration with Tribal partners and NPS and will contribute directly to the multi-cultural, multi-disciplinary research project currently envisioned by the Pueblo of Zuni and Grand Canyon National Park.

A specific budget for this project element has not been defined, pending additional discussion with Tribes and NPS about the scope and timing of the archaeological excavation project; however, it is anticipated that the work described above can be accomplished within the scope of the current Project D budget by partially reprograming PIs time and salary from elements D.1 and D.2 to accomplish the proposed mapping, field studies, and final write-up of results for D.4.

The following is a time schedule for this project:

- FY2021: Contribute to consultation, development, and reviews of a multi-cultural, multi-disciplinary research design.
- FY2022: Conduct baseline mapping, prepare baseline topographic map for use by archaeologists; conduct geo-archaeological and geomorphological field research in collaboration with other project personnel.
- FY2023: Prepare at least one chapter for the final archaeological report (other products TBD)

5.2. Outcomes and Products

Project Element D.1.

- Annual reports on the status of the vegetation removal experiment and related monitoring conducted under Element D.1. Submit to the GCDAMP at the end of Fiscal Years 2021, 2022, and 2023.
- Presentation on the outcome of vegetation removal experiment at the Annual Reporting Meeting in calendar year 2023 (e.g., January 2023).
- Journal article on the results of the vegetation removal experiment. Prepare and submit to the journal for peer-review in FY2023.
- USGS report summarizing the results for Element D.1 monitoring conducted during all the three years (FY2021-23) of this work plan. Prepare and submit to USGS for peer-review in FY2023.

Project Element D.2.

- USGS Professional Paper on results of the Birdseye repeat photography study (FY2022).
- Peer-reviewed journal article on Goldwater photo matching study (FY2023).
- Photo-matches will be served via GCMRC’s website (FY2023).
- Annual presentation at the Annual Reporting Meeting.

Project Element D.3.

- Published report on the history of GCDAMP cultural program (FY2023).
- Interview transcripts and supporting documents served via a web platform.

Project Element D.4. **(not funded)**

- Collaborative knowledge sharing among multi-disciplinary scientists and multi-cultural Tribal members.
- Chapter and map figures in the final published report on excavation of AZ C:13:339.

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7. Budget

Fiscal Year 2021								
Project D Effects of Dam Operations and Vegetation Management for Archaeological Sites	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
D.1. Dam operation and vegetation management effects for archaeological sites	$193,851	$6,400	$7,000	$18,850	$0	$0	$31,654	**$257,755**
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$28,707	$5,000	$500	$0	$0	$0	$4,789	**$38,996**
D.3. Cultural program administrative history	$22,966	$1,000	$300	$0	$0	$0	$3,397	**$27,663**
Total Project D	**$245,523**	**$12,400**	**$7,800**	**$18,850**	**$0**	**$0**	**$39,840**	**$324,413**

Fiscal Year 2022								
Project D Effects of Dam Operations and Vegetation Management for Archaeological Sites	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
D.1. Dam operation and vegetation management effects for archaeological sites	$184,803	$500	$150	$19,174	$0	$0	$45,018	**$249,645**
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$29,281	$150	$0	$0	$0	$0	$6,475	**$35,906**
D.3. Cultural program administrative history	$23,425	$0	$0	$0	$0	$0	$5,153	**$28,578**
Total Project D	**$237,509**	**$650**	**$150**	**$19,174**	**$0**	**$0**	**$56,646**	**$314,129**

Fiscal Year 2023								
Project D Effects of Dam Operations and Vegetation Management for Archaeological Sites	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
D.1. Dam operation and vegetation management effects for archaeological sites	$186,879	$600	$850	$19,507	$0	$0	$58,194	**$266,030**
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$41,813	$250	$50	$0	$0	$0	$11,792	**$53,905**
D.3. Cultural program administrative history	$0	$0	$0	$0	$0	$0	$0	**$0**
Total Project D	**$228,692**	**$850**	**$900**	**$19,507**	**$0**	**$0**	**$69,986**	**$319,935**

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

1. Investigators

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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, 2020). 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 (Yackulic, 2020). While total primary production is not significantly related to metrics of fish production in Glen Canyon, the availability of phosphorus (P), an important limiting nutrient, is correlated with chlorophyll *a*, a metric of diatom and other non-macrophyte-based primary production. Furthermore, P 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) (U.S. Department of Interior, 2016; Yackulic, 2020).

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 Interagency Lake Powell Water Quality Monitoring project (Appendix 1), Project A.2, and Project E) with improved additional information about phosphorus, gas transfer and the relative role of diatoms in affecting whole river production (Elements E.1 and E.2). Project E is 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.

Key to linking primary production to higher trophic levels is developing a better understanding of how much production is required to meet fish metabolic demands. This understanding will help us to develop ecosystem models that incorporate data collected at multiple trophic levels (Element E.3). Element E.3 involves both laboratory work and ecosystem modeling. Laboratory work will quantify the standard and active metabolic rates of the dominant native fishes in the ecosystem (i.e., humpback chub and flannelmouth sucker). Past bioenergetics work done in the 2000s (Petersen and Paukert, 2005; Paukert and Petersen, 2007) assumed humpback chub had metabolism like other *Gila spp.* because it has never been directly measured in humpback chub.

However, recent observations in both the lab and the field suggest that humpback chub may have abnormally low metabolisms that enable them to persist through periods of food shortage (e.g., Dibble and others, 2017). By estimating these standard and active metabolic rates 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 through an ecosystem model.

3. Hypotheses and Science Questions

Below we list the specific hypotheses this project addresses organized by project element. Hypotheses are numbered for easier reference throughout the remainder of the project proposal.

Element E.1:

- H1: Glen Canyon Dam outflow is the biggest control on P concentrations in Glen Canyon and Marble Canyon, but this influence is dampened the further you move downstream (and with storm-based tributary inflows).
- H2: The relationship between Colorado River silt and clay concentration and total P extends to the soluble reactive P pool.
- H3: There is a relatively constant relationship between water column silt and clay concentration and total P concentration in the tributaries to the Colorado River through Grand Canyon.
- H4: A large fraction of the sediment P pool is calcite bound.
- H5: We expect equilibrium P concentrations in the Colorado River to range from 1-10 $\mu g\ L^{-1}$ and to be highest in finer, backwater sediments.
- H6: Lower pH leads to elevated water column P bioavailability due to P release from calcium carbonates in the sediment.

Element E.2:

- H7: Silt and clay concentrations negatively affect instantaneous gross primary production (GPP) via reductions in light availability.
- H8: High concentrations of silt and clay in the water column have a lagged positive effect on GPP via utilization of P bound to deposited silts and clays once the water is clear again.
- H9: The proportion of GPP in the river due to diatom versus macrophyte production varies both seasonally and due to outflow P concentrations in Glen Canyon.

- H10: Macrophyte species composition and cover in Glen Canyon shifts in response to flow, temperature, and nutrients.

Element E.3:

- H11: Humpback chub and flannelmouth sucker have lower basal metabolic demands than related taxa.
- H12: This low metabolic demand means the ecosystem can sustain large populations of these species despite relatively low primary production and that these species can survive through relatively extended periods of low food availability.

4. Background

General Background

Given several challenges associated with quantifying primary production directly below dams, the majority of what we currently know about controls on riverine primary production comes from unregulated rivers and streams or river reaches far down-river from dams (Bernhardt and others, 2018). In these systems light and disturbance are key factors determining the timing and overall rate of primary production. Glen Canyon Dam has fundamentally altered the light and disturbance regimes in the downstream Colorado River. Since damming, the river has experienced a 95% decline in the amount of fine sediment delivered to the upstream boundary of Grand Canyon National Park (Topping and others, 2000) resulting in much less turbid conditions during much of the year through Marble and Grand Canyon (e.g. downstream of the Paria River) and extremely clear water conditions year-round in Glen Canyon (e.g. < 2 Nephelometric Turbidity Units with the exception of a rare turbidity interflow event from the dam; Wildman and Vernieu, 2017). Disturbance regimes have also shifted.

Damming has shifted the hydrograph from large seasonally driven fluctuations in discharge to large sub-daily variation and muted seasonal variation in discharge related to hydropower production. Consistent with work in unregulated rivers, previous modeling work in the Colorado River upstream of Diamond Creek showed that riverine primary production is strongly light limited and that higher diel discharge fluctuations lead to somewhat less primary production (Hall and others, 2015). Initial findings from the 2018 and 2019 “Bug Flow” experiments suggest that low and steady flows significantly increase reach-scale rates of primary production (Figure 1).

On top of these flow and light effects, primary production modeling in the reach upstream of the Little Colorado River shows that nutrients (e.g., soluble reactive P) can be just as important a lever as is light to overall riverine primary productivity (Deemer, 2020 Annual Reporting Meeting presentation, Figure 2). This makes sense given the extreme degree of P retention that occurs in Lake Powell (wherein less than 5% of the P entering the reservoir makes it downstream; Gloss, 1977).

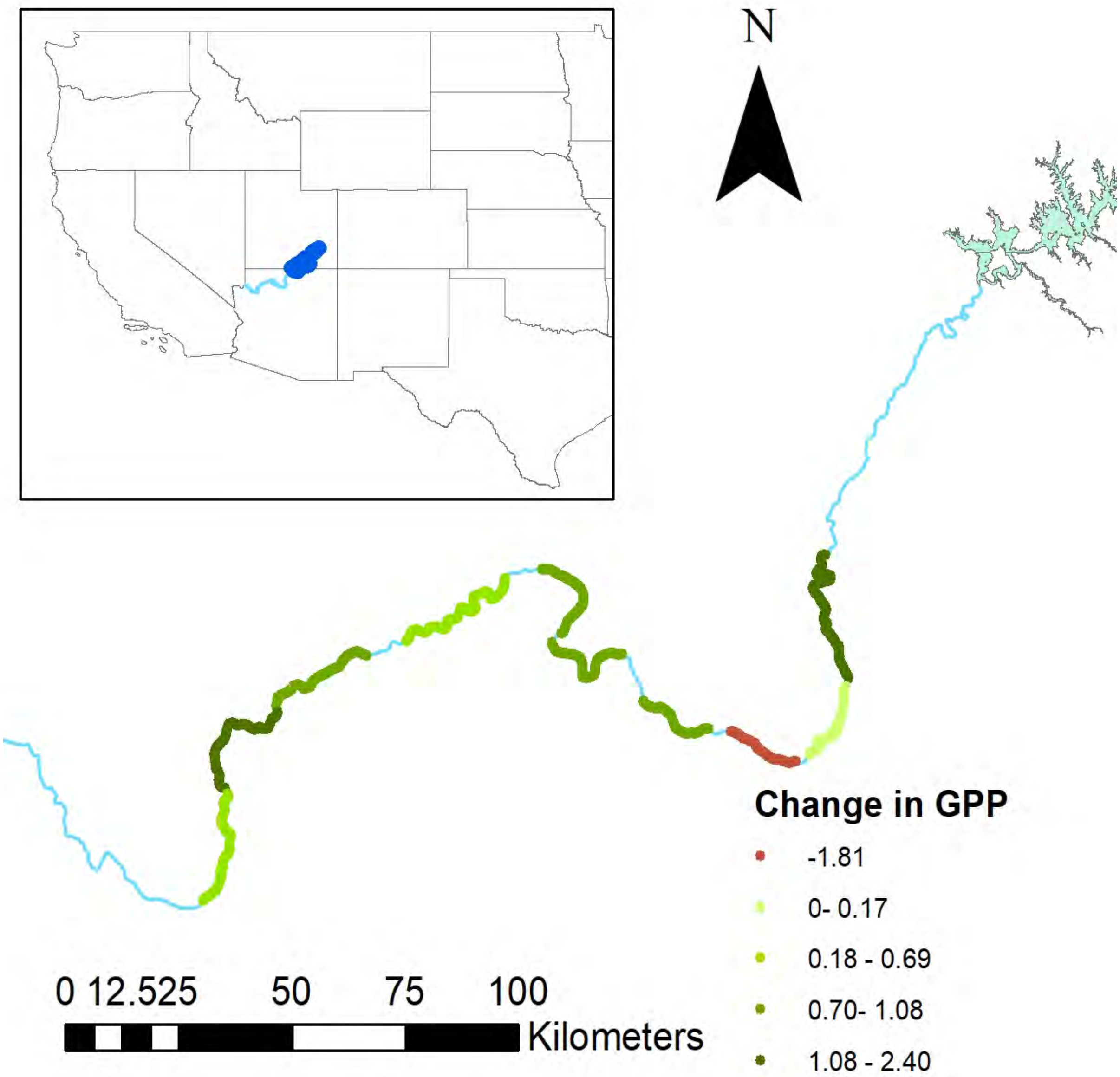

Figure 1. Relative increase (green) or decrease (red) of gross primary production rates from the weekday to the weekend at 10 reaches on the Colorado River in May and June of the 2019 "Bug Flow" experiment. The experiment maintained normal load following flow during the weekdays and adjusted to low and steady flows during the weekends. 9 out of 10 reaches experienced elevated gross primary production (GPP) on the weekend low and steady flow, relative to the weekday load following flow. GPP is in units of g O_2 m^{-2} d^{-1}. Preliminary data, subject to revision.

Factors affecting spatio-temporal variation in phosphorus in the Colorado River Ecosystem

While there is temporally and spatially resolved information about riverine turbidity, solar inputs, discharge, and gross primary productivity (via continuous oxygen and temperature measurements) in the Colorado River Ecosystem (CRe), there is much less information about spatio-temporal variability of P and other nutrients in the river. Longitudinal sampling during the FY2018-20 Triennial Work Plan revealed little variability in background soluble reactive P concentrations, likely due to the extremely low background concentrations throughout the river (often below detection). Initial storm-based P sampling in the Paria River suggest that it can contribute significantly to the Colorado River's annual total P budget, and that dissolved bioavailable forms of P are also elevated during storms. Still, the degree of storm-to-storm variability appears quite high, with peak storm total P concentrations ranging between 5 and 30 mg L^{-1} in the two storms sampled thus far (August 2018 and November 2019). We expect that Glen Canyon Dam outflows dominate the riverine P budget for in Glen Canyon, Marble Canyon and Eastern Grand Canyon, but that tributary inputs become more important in western Grand Canyon as well as throughout the river during storms (H1).

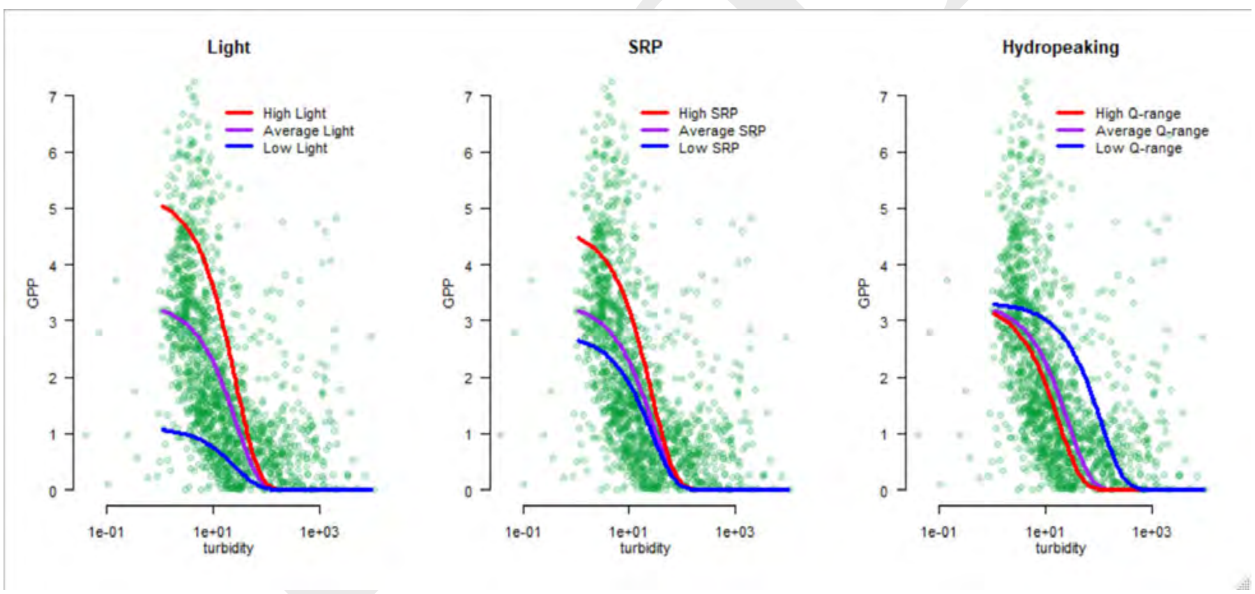

Figure 2. Rates of gross primary production (GPP) across a range of turbidity values in the river reach above the Colorado River above Little Colorado River (gage 09383100). The lines represent the relationship between turbidity and gross primary production across high, average, and low light conditions (left), soluble reactive phosphorus (SRP) concentrations released from Glen Canyon Dam (middle), and sub-diel fluctuations in discharge (right). The red line shows average GPP response to a high light, SRP, or hydropeaking regime, whereas purple lines show response to medium scenarios and blue shows response to low scenarios. SRP at the outflow of Glen Canyon Dam is a similarly strong lever on GPP as is light availability ~120 km downstream. GPP is in units of g O_2 m^{-2} d^{-1} and turbidity is in Nephelometric Turbidity Units. Preliminary data, subject to revision.

Long term water quality monitoring in the Colorado River near Phantom Ranch (gage 09402500) and the Colorado River upstream of Diamond Creek (gage 09402500) show a strong relationship between suspended silt and clay concentrations and total P (Figure 3). We expect that there is also a positive relationship between suspended silt and clay and soluble reactive P (H2). If similar predictable relationships exist between silt and clay concentrations and P concentrations in the Paria River and other tributaries (e.g., Little Colorado River, H3), then P input budgeting could be hindcast (possibly using information about either the time of year or the storm location in the watershed).

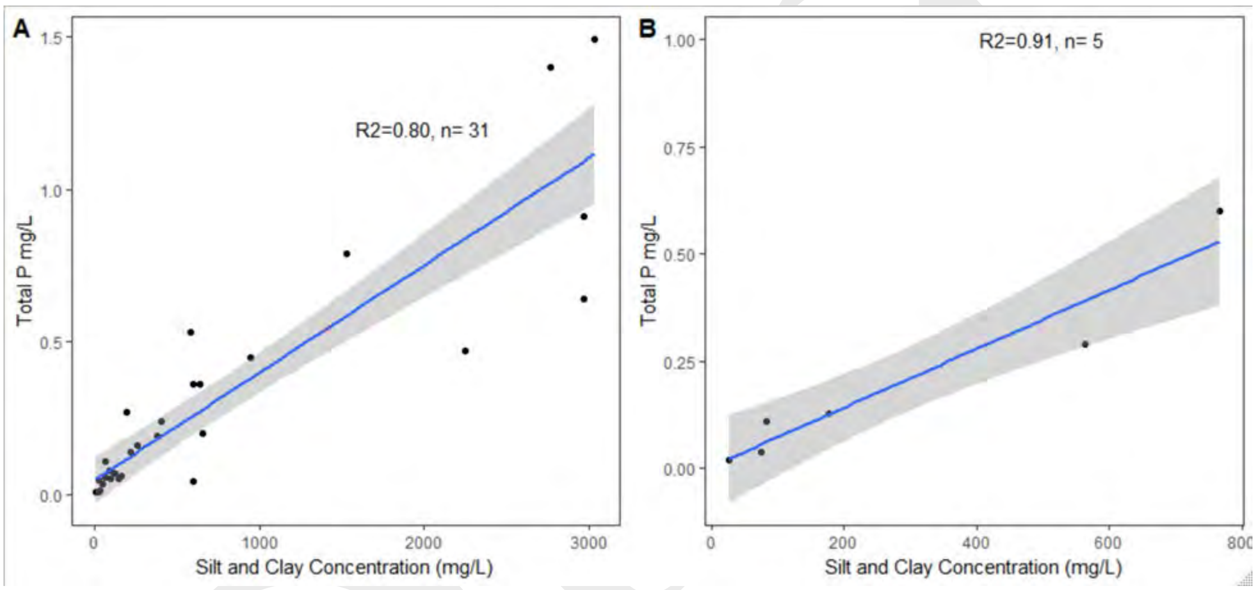

Figure 3. Physical silt and clay measurements predict total P concentrations at two long-term gage sites on the Colorado River: upstream of Diamond Creek (panel A, gage 09404200) and near Phantom Ranch (panel B, gage 09402500). Measurements at the Colorado River upstream of Diamond Creek were taken between 1989 and 2019. Less data is available at the Colorado River near Phantom Ranch and ranges from 2014-2019. Preliminary data, subject to revision.

The potential importance of tributary P inputs is highlighted by both the seasonal and spatial breakdown of relationships between P release from Glen Canyon Dam and downstream rates of GPP. It is currently unknown whether the relationships between silt and clay concentrations and total P extend to the biologically available pool of P (H2), as well as how accessible this P may be to producers given its co-occurrence with high turbidity (and thus low light availability for photosynthesis, H5 and H7). While biological phosphate uptake rates often scale with light availability, some species of primary producers can store relatively large amounts of P even under dark conditions (Simonis and others, 1974; Sun and others, 2015), whereas dark conditions inhibit P uptake in other primary producer species (Chisholm and Stross, 1976).

The extent to which P supplied by tributary storm inputs can be immediately incorporated by primary producers (and their bacterial associates) will help determine (together with sediment P sorption capacity) the role of storms in affecting whole-ecosystem primary productivity and is an important area for research. If the relative P uptake scales with total P concentrations (rather than scaling with light or being dependent on a watershed source), then existing estimates of silt and clay concentrations throughout the river should help disentangle the lagged effect of storm-based inputs on primary production (H8).

The quality of river sediment also influences the capacity for the river to take up storm-based pulses of P. Given a sediment's minerology and organic matter content, there is an equilibrium P concentration (EPC) where the concentration of P in the water column is in dynamic equilibrium with concentration of the P in sediments (Mayer and Gloss, 1980; Zhang and Huang, 2007). At a reservoir site located near the inflow to Lake Powell, EPCs were six orders of magnitude higher than the river concentrations typically observed in the Colorado River below Glen Canyon Dam (EPC= 2000 mg L^{-1} Soluble Reactive P [SRP]; Mayer and Gloss, 1980). Still, more recent equilibrium P analyses in the Colorado River inlet to Lake Powell report much lower EPCs (1.5 to 11.5 µg L^{-1}), with values dropping as you move away from the inlet and into the main body of the reservoir (Wildman and Hering, 2011). This work also found that finer sediments had higher EPCs (Wildman and Hering, 2011), consistent with a predictable relationship between water column P and silt and clay (H3 and H4). We expect EPC of Colorado River sediments to be similar to the lower end of EPCs in Lake Powell, with higher EPCs in finer backwater sediments than in the main channel (H5). In most cases, we expect EPCs to support some degree of sediment P uptake associated with storm P pulses.

The location of available P (water column or sediment) likely exerts an important control on the species composition and cover of primary producers that dominate the riverbed. In Glen Canyon for example, macrophytes have direct access to sediment P whereas the more desirable food source for higher trophic levels (i.e., diatoms) rely on dissolved P concentrations in the water column. The independent P cycling of a rooted macrophyte and its algal epiphytes can be quite pronounced. In one study the rooted macrophyte *Najas flexilis* derived 99% of their P from sediment and released only about 2% of this P to epiphytes and the water column, although some small adnate epiphytes did source ~60% of their P from the host macrophyte (Moeller and others, 1988). At Lees Ferry, GPP is not correlated with P concentrations, but chlorophyll *a* is modestly correlated with P concentrations. We hypothesize that, as P increases in the water column, diatom communities increase and colonize macrophyte stems and leaves. This colonization shades the plant from sunlight, such that primary production from rooted plants will decrease (H9). As such, the proportion of GPP in the river due to diatom versus macrophyte production likely varies both seasonally and due to outflow P concentrations in Glen Canyon. Since diatoms are a preferred food source for secondary producers (i.e., macroinvertebrates; Wellard Kelly and others, 2013), changes in P concentrations have important implications for how primary production is incorporated into higher trophic levels.

Over time, changes in P availability and other factors (e.g., flow regime, temperature) may also have driven long-term changes in algal and macrophyte composition and cover in Glen Canyon (H10). This change in macrophyte communities from a community dominated by other high-quality algal resources (i.e., *Cladophora*) to one dominated by bryophytes and *Potamogeton* have important implications for river food webs. Work proposed in E.2 aims to better understand the current macrophyte community in Glen Canyon as a baseline for potential future changes in composition due to dam operations, including experimental flow releases (see Project Element E.4).

Finally, the pH of Lake Powell outflows and large tributary inflows may exert an important control on riverine P availability independent of the P outflow concentration (H6). Calcite precipitation in Lake Powell reduces pH buffering in the Colorado River (Deemer and others, 2020) making the river more vulnerable to a sustained decline in pH. In addition, the easily exchangeable fraction of sediment P (that plays into the determination of EPC), P can be bound to various minerals and to organic matter in the sediment. Lake Powell sediments are high in calcite bound P (Wildman and Hering, 2011), a pool that can be dissolved and re-released to the water column when pH drops (Corman and others, 2016). We expect large pools of calcite-bound P in Colorado River sediments, and especially in Little Colorado River sediments (H4; Wildman and Herring, 2011). In locations where calcite-bound P makes up a large fraction of the sediment P reservoir, low pH events may cause biologically significant release of P (H6).

Challenges and opportunities for identifying the controls and patterns of riverine primary production

Despite an array of high-quality dissolved oxygen loggers in the river, challenges also exist with estimating primary production. One problem stems from the way that sub-daily discharge fluctuations and sub-daily fluctuations in turbidity affect primary producers. Most approaches to estimating primary production scale sub-daily primary production to light at the water's surface, implicitly assuming that the amount of attenuation that occurs in the water column before light reaches primary producers is a constant proportion over the course of a day. However, in a regulated river with large fluctuations in discharge and turbidity like the Colorado River, this assumption is regularly violated. We have been involved recently in developing process error-based metabolism models that allow for sub-daily partitioning of gross primary production independent of sub-daily changes in light availability. Initial application of these models show promise for an improved understanding of controls on primary production in the Colorado River (Figure 1).

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

While it is well established that fish are often food limited in the Colorado River downriver of Glen Canyon Dam (Cross and others, 2011), we lack a quantitative understanding of how food limitation varies over time and space and how it impacts different fish species.

Food limitation can be defined formally as conditions when the energy produced by lower trophic levels and transferred to higher trophic levels does not meet demand from higher trophic levels. Element E.2 focuses on identifying the causes of variation in the production of energy at the base of food webs; however, to understand impacts on fish, we also require estimates of how demand varies. Quantifying demand requires estimates of abundance across different size classes and species of fish within a given reach, as well as the metabolic needs associated with growth in weight over a given time interval.

In Glen Canyon, recent work has begun to quantify this demand for rainbow trout to better understand (and eventually predict) trends in rainbow trout demography (M. Yard, unpublished data). These calculations rely not only on field measurement, but also on lab-based estimates of metabolic needs, which are well-studied for a species like rainbow trout. For other species, like flannelmouth sucker and humpback chub that dominate downstream biomass estimates, we lack direct estimates of metabolism and bioenergetics assessments have often relied on lab estimates for related taxa.

This approach to estimating metabolism is problematic as there is evidence to suggest that species found in Grand Canyon may have much lower metabolic needs than related species. For example, Dibble and others (2017) found that humpback chub held without food for 45 days did not significantly decrease in condition, while bonytail and roundtail chub declined significantly – an observation that has been noted by others doing experimental work with humpback chub (K. Gido, pers. comm.). Quantifying this demand is important for understanding recent increases in populations of native fish species in western Grand Canyon and determining potential limits to future population growth. If humpback chub and other native species in Grand Canyon have lower metabolic demands (H11) they will require substantially less food to maintain a given weight, and it may be possible to sustain much large biomasses (abundances) of native fish at a given food availability (H12). If these species have lower metabolic demands, it may also explain why declines in food availability have been associated with different demographic responses in native fish as compared to rainbow trout.

Based on the life history of species, they often respond demographically in different ways when food availability increases or decreases. For rainbow trout, it appears that annual changes in food availability directly impact fish condition and growth, which in turn impacts reproduction. When food is abundant, survival of all sizes of rainbow trout is higher. When food supply declines, however, large fish face high metabolic deficits. Among native fish, we have observed similar changes in fish condition and perhaps reproduction; however, impacts on growth and survival are either smaller or masked by effect of environmental factors. As a result, adult abundances of native fish appear to be more stable in response to declines in food availability, but reproduction is quite variable.

5. Proposed Work

5.1. Project Elements

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

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Theodore Kennedy, Research Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Sasha Reed, Research Ecologist, USGS, SBSC

This project element will expand current monitoring of tributary 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 bioassays 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. Sediment P sampling, P sorption experiments, and incubations 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 sections further downriver where tributary inputs potentially override the influence of variation in the SRP in dam releases) via modeling in element E.2.

Objectives

1) Construct a P budget for the Colorado River between Glen Canyon Dam and Lake Mead, constraining baseflow and storm P inputs from tributaries.
2) Further develop relationships between suspended silt and clay concentrations and P.
3) Determine sediment P concentrations throughout the Colorado River and in the Little Colorado River. Determine the speciation of this P as either loosely-sorbed, iron bound, calcite bound, detrital apatite bound, or organic bound.
4) Quantify sediment P uptake/release capacity for the Colorado River through Glen, Marble and Grand Canyons as well as in the Little Colorado River. Examine how changing chemical/physical conditions may affect the sediment P reservoir.

Methods

This project will consider major sources and potential sinks for P in the CRe using a P mass balance approach (in the spirit of Meyer and Likens, 1979). P loading from different potentially important sources will be estimated and compared to estimates of P output as measured at the gate at the Colorado River upstream of Diamond Creek. This effort will rely on a combination of direct P measurements and modeling. Sediment incubations (and findings from mass budgeting) will help better constrain the potential importance of sediment P cycling in the overall riverine budget. Below, we describe methods associated with estimating: 1) dam inflows, 2) large tributary inflows (Paria and Little Colorado rivers), 3) smaller tributary inflows, 4) outflows, and 5) rates of sediment P cycling.

We hypothesize that P loading from the dam will be the predominant source of P in the upper portions of the river during most times, but that tributaries will be increasingly important at further downstream locations (H1). Monthly measurements at the outflow to Glen Canyon Dam are currently taken as part of the Interagency Lake Powell Water Quality Monitoring Program (Appendix 1). These measurements will be used in combination with discharge to estimate P loading from the dam. Given the uncertainty associated with single P measurements, we will use these measurements together with QA/QC results (from equipment and reagent blanks) to train a seasonal model of P.

Water sampling will be conducted to assess the concentrations of SRP, total dissolved phosphorus [TDP], and total phosphorus in both the mainstem Colorado River and its tributaries. This will include preservation tests (filtering water in the field vs. the lab and freezing water in the field vs. the lab) to determine the relative effects on P dynamics. Refrigerated ISCO samplers on the Paria River at Lees Ferry (gage 09382000) and the Little Colorado River near Cameron (gage 09402000) will be used to sample winter and monsoon storms. These samples will be supplemented with baseflow grab samples to support a whole-year estimate of P inputs from these larger tributary systems. In smaller tributaries, a citizen science approach will be used to capture P concentrations at baseflow and during storm conditions. We will focus on gaged tributaries where concentration estimates can easily be translated into P loads. These are: Kanab Creek above the mouth (gage 09403850), Bright Angel Creek near Grand Canyon (gage 09403000), Havasu Creek above the mouth (gage 09404115), Badger Creek below Highway 89A (gage GCMRC-MCLT1), Shinumo Wash in 29 Mile Canyon (gage GCMRC-MCLT6), House Rock Wash below Emmett Wash (gage GCMRC-MCLT4), and North Canyon near Cliff Dwellers (GCMRC-MCLT5). At the gages on the Colorado River near Phantom Ranch and the Colorado River upstream of Diamond Creek, targeted sampling during a range of conditions will be used to improve the precision on long-term relationship between total P and suspended silt and clays (which are already continuously monitored at the Colorado River upstream of Diamond Creek gage).

In addition, measurements of the more bioavailable forms of P (SRP and TDP) will test whether this relationship extends to the most biologically relevant fractions of the P pool (H2). Once these relationships are developed, we will also use them to inform primary production models (H7 and H8). We expect that the relationship between suspended silts and clays and P will become more important in predicting total P availability at sites further downstream from the dam.

Efforts to better understand P dynamics in riverine sediments will include:

1) Sequential extractions of sediment-bound P pools to quantify both the quantify and form of P in Colorado River sediments,

2) P sorption assays with backwater, channel margin, and main channel Colorado River sediments to determine EPCs of Colorado River sediments, and

3) Targeted sediment incubations under varying pH and dissolved oxygen conditions that will aim to quantify the controls on sediment P cycling (uptake and/or release).

Sequential extractions and P sorption assays will be done on riverine sediments following the methods of Wildman and Hering (2011) at long term Sonde sites where GPP estimates have been made including: the Colorado River at Lees Ferry, the Colorado River near river mile 33 (gage 09383050), the Colorado River upstream of the Little Colorado River (gage 09383100), the Colorado River near Phantom Ranch, the Colorado River upstream of National (gage 09404120), the Colorado River upstream of Diamond Creek, the Paria River at Lees Ferry, and in the Little Colorado River near the mouth (gage 09402300). Sediment incubation experiments will be done at fewer locations—comparing sediments from the Colorado River at Lees Ferry, the Colorado River upstream of Diamond Creek, the Paria River at Lees Ferry and the Little Colorado River near the mouth.

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

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Charles Yackulic, Research Statistician, USGS, GCMRC

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 proposed here, 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 2021, we plan to repeat map the vegetation in Glen Canyon if maintenance flows occur. In addition, we plan to determine the proportion of primary production in Glen Canyon that is derived from diatoms, as opposed to macrophytes.

Objectives

1) Develop a mechanistic GPP model that can utilize information about ambient turbidity, outflow P, temperature, silt and clay (as a potential proxy for nutrient availability), and solar irradiance to better quantify the relative importance of these different variables on overall production.
2) Quantify the relative contribution of diatoms vs. macrophytes to Glen Canyon GPP under a variety of conditions.
3) Continue to document shifts in the vegetation community in Glen Canyon, repeat mapping vegetation in 2021 if maintenance flows occur (see Experimental Project Budget E.4).

Methods

Overall, this project element focuses on:

1) Measuring rates of gross primary production, or the total rate at which oxygen is produced via *in situ* photosynthesis,
2) Relating primary production to environmental drivers, and
3) Understanding the current composition and distribution of different vegetation types under various environmental conditions.

A rapidly developing body of work uses models to estimate gross primary production based on continuous records of dissolved oxygen together with information about reach scale light availability, discharge, temperature, and depth (Bernhardt and others, 2018; Appling and others, 2018).

In high gradient mountain streams and whitewater rivers as well as in systems with low rates of production, the model additionally requires an estimate of gas exchange since the gas exchange dynamics are more complex and/or difficult to detect against low background GPP signal (Hall and Ulseth, 2020). Previous work supports gas exchange estimates from the dam down to Diamond Creek (Magirl and others, 2005; Hall and others, 2012).

We will continue the seasonal deployment of MiniDOT oxygen loggers that began in spring of 2018 and the year-round deployment of YSIs at -8 mile in Glen Canyon and at Lees Ferry. These loggers support GPP modeling in reaches not covered by the long term YSI deployments in Project A (e.g., the Colorado River near river mile 33, the Colorado River upstream of the Little Colorado River, the Colorado River near Phantom Ranch, the Colorado River upstream of National, and the Colorado River upstream of Diamond Creek). MiniDOTs are deployed based on oxygen turnover reaches such that they "map" patterns in gross primary production for a total of 139 river kilometers between 60 mile and Diamond Creek (Figure 1), with two additional MiniDOTs deployed below Diamond Creek (not depicted in Figure 1). These MiniDOTs will document primary productivity during the most productive times of the year (April-September) and during experimental macroinvertebrate production flows (if they continue into the future during the same time of year as is currently implemented).

Mechanistic gross primary production modeling efforts will aim to expand on the relationships developed in Project Element E.1 between silt and clay concentrations and available P to inform modeling of riverine GPP. We anticipate that silt and clay data will reveal lagged effects of storm P inputs, wherein downstream patterns in GPP may largely be explained by the bottom-up P lever. We will also expand on previous efforts to estimate soluble reactive P loading from Glen Canyon Dam, using QA/QC information to develop seasonal estimates of soluble reactive P outflow each year to feed the model.

In Glen Canyon, where patterns of GPP appear disconnected from aquatic insect and fish production, we aim to characterize the relative contribution of diatoms and macrophytes to total GPP. Our hypothesis is that during periods of high dissolved P availability in Glen Canyon, diatoms have a competitive advantage, increasing in density as epiphytic algae that grows on rooted macrophytes. This excess growth on the stems and leaves of macrophytes shade the plants from direct sunlight, resulting in a decrease in oxygen production from macrophytes and a higher contribution to GPP from diatom production (H9).

The first step in this process is to conduct a series of light-dark bottle experiments in the field during the spring and summer of 2021, with macrophyte and aquatic macroalgal species collected from the riverbed with varying loads of diatoms. Since P concentrations are slightly higher near the dam, we will stratify samples by river location.

Target macrophytes include the dominant macrophyte and macroalgal species identified in an ongoing vegetation mapping project (see Objective 3 in E.2), including (but not limited to) *Chara*, *Potamogeton*, *Cladophora*, and bryophytes. Macrophyte samples of approximately the same biomass will be incubated in glass bottles at the river edge to measure rates of NPP, ER, and ultimately GPP using a hand-held oxygen probe. Since New Zealand mud snails (*Potamopyrgus antipodarum*) are hypothesized to have a strong top-down effect on diatom availability in Glen Canyon for other secondary consumers, we propose to add a second set of experiments with and without mud snail treatments (at varying densities of mud snails) to understand how grazers influence diatom communities, and following, how grazers may be influencing GPP at Lees Ferry through changes in macrophyte shading. Following GPP measurements in the field, macrophyte samples will be brought to the laboratory, sonicated to remove diatoms, and oven dried. Relative diatom load will be compared to GPP per unit of vegetation biomass and mud snail density.

The purpose of the aquatic vegetation survey project is to develop a semi-automated aquatic vegetation classification system using underwater imagery combined with the use of machine learning and deep convolutional neural networks to detect annual to decadal scale changes in vegetation cover and species composition in the Colorado River downstream from Glen Canyon Dam. This project will facilitate detection of change at the base of the food web relative to various ecosystem drivers (nutrients, temperature and discharge).

This project commenced in the FY2015-17 work plan, during which we made several advances toward developing a protocol for low-cost surveys of submerged vegetation in Glen Canyon. This included developing a new HD underwater video camera system for geolocated video observations of the bed, and using these observations to: 1) observe vegetation types at the genus or species level, as well as the depth and substrate they are growing at/on; and 2) develop a high-resolution vegetation mapping system based on acoustic backscatter measured by multibeam sonar.

We refined this approach in the FY2018-20 work plan by: 1) developing and/or utilizing image processing software options (Python, MakeSense.ai) to classify cover and vegetation types in underwater imagery (see Figure 4 for classification example using Python), 2) creating image labels by manually classifying vegetation types in a series of images captured during August 2016 and June 2019 trips, 3) developing a library of images to feed into the model framework, and 4) running segmentation models on imagery. This model will be used to automatically classify thousands of underwater images from sampling events in 2016 and 2019 and can be used in the future to detect change in the CRe over time. Available imagery to date includes >50,000 photos of underwater vegetation, of varying quality.

For the FY2021-23 work plan, in lieu of collecting more imagery, we propose to analyze existing imagery sources from two permanent transects we established in Glen Canyon from 2016-2019 (i.e., the 'upper' reach ~ -13 mile and the 'lower' reach ~ -4 mile). Since macrophyte communities likely change gradually over time in the absence of large disturbance events (but see Experimental Fund Request, E.4), we propose to take repeat imagery every few years rather than on an annual basis. Our focus on analyzing existing imagery, refining the models, and publishing results in peer-reviewed literature is an important step in any future data collection effort.

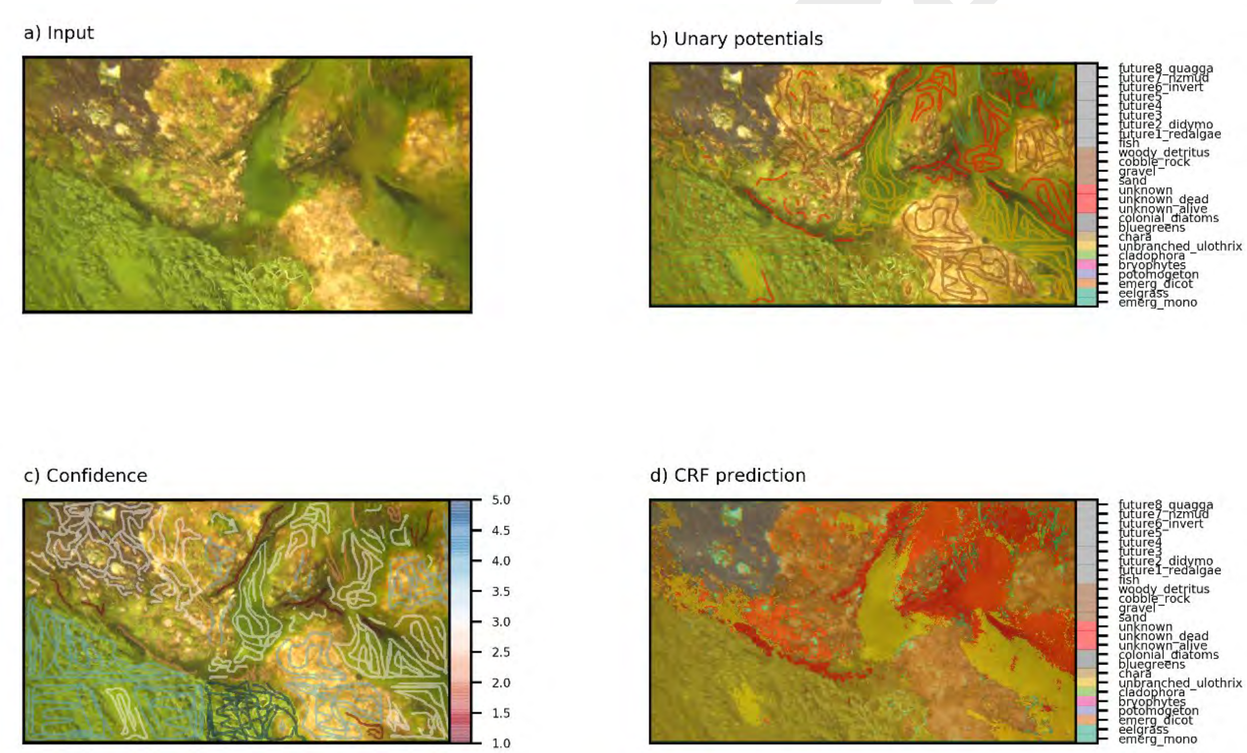

Figure 4. A visual example of manual classification of an underwater image, and model prediction of cover by species using Python software. a) Underwater image taken in Glen Canyon (i.e., the input file); b) Manual on-screen image annotations that classify vegetation types at the pixel level (i.e., unary potentials); c) Confidence assigned to each unary potential by the manual annotator in "b"; and d) Predictions of vegetation cover classes using conditional random fields (CRF), a classification and graphical modeling technique.

Project Element E.3. Productivity at Higher Trophic Levels

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We will combine absolute fish population abundances estimated from fixed sites (i.e., in Glen Canyon, Juvenile Chub Monitoring (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 standard and active metabolic rates to develop ecosystem models. For the latter, acquiring a better understanding of respiratory physiology and the energy necessary for basic physiological functioning will provide better context for the effects of changes in dam operations and environmental conditions on the growth and production of native species (Chabot and others, 2016a).

The Metabolic Rate (MR) of fishes is influenced by factors including body size, water temperature, activity level, consumption/food intake, physiological state, and anabolism (Chabot and others, 2016b). The basal, or Standard Metabolic Rate (SMR) represents the minimum amount of energy needed for a fish to persist in its environment at a given temperature and does not include the added energy needed for growth, digestion, activity, and reproduction. Below SMR, physiological function in fishes is impaired and usually leads to mortality. Active Metabolic Rate (AMR) is at the other end of the spectrum and represents a fish's maximum aerobic metabolic rate at a specific temperature. The difference between SMR (minimum) and AMR (maximum) provide an indication of the total amount of energy available to fish (Chabot and others, 2016b; Norin and Malte, 2011).

Laboratory experiments will be used to determine the standard and active metabolic rates of large-bodied native fish in the Grand Canyon (i.e., humpback chub and flannelmouth sucker) that dominate the biomass of fish communities and for which there are no literature values. These data will be integrated into an aquatic ecosystem model that seeks to understand dynamics of fish communities throughout different reaches of the Grand Canyon from an energetic perspective. This modeling will integrate primary production 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.

Objectives

1) Measure standard and active metabolic rates of fishes under laboratory conditions for humpback chub and flannelmouth sucker, as past studies have relied on related species that may not be reliable surrogates.

2) Integrate data in ecosystem models to better understand how nutrients, flow and discharge directly and indirectly affect other trophic levels.

Methods

Measuring metabolism in controlled laboratory settings is relatively simple. Standard and active metabolic rates are quantified by measuring oxygen removal from the water column (i.e., measured oxygen uptake, MO_2, or respiration) by fish, and then converting oxygen uptake to units of energy used. Fish specimens of varying sizes will be selected from laboratory-grown stock housed at the U.S. Forest Service Rocky Mountain Research Station. Humpback chub and flannelmouth sucker will be kept in recirculating tanks at ambient temperatures and fed a maintenance diet until trials commence. Standard metabolic rates of marked individual fish will be measured using automated intermittent closed respirometry. Briefly, replicates of closed acrylic respirometer chambers will be submerged in multiple temperature treatments representing the current and potential future thermal regime of the Colorado River in Grand Canyon. An ultraviolet sterilizer of flow-through water will be used to minimize respiration from bacteria in the water column. Fully aerated water will be introduced into each chamber via a pump. Individual fish will be placed in each chamber and respiration continuously measured via oxygen electrodes for up to 24 hours per trial. Active metabolic rates will be measured in a similar manner in either a flow-through recirculating tank system, or by chasing of the specimen before placement in each chamber. Multiple size classes of humpback chub and flannelmouth sucker will be used in this experiment to allometrically scale metabolic rates. Individual pit-tagged fish will undergo multiple trials to assess repeatability.

Ecosystem models will be built by coupling seasonal estimates of GPP, invertebrate drift, and fish populations in a series of difference equations that treat transfer efficiencies as random effects informed by intensive food web studies and ongoing diet studies. This work will expand on efforts already made to estimate the amount of invertebrate consumption required to support observed variation in rainbow trout biomass and growth in Glen Canyon by extending this approach to the more diverse fish communities found in the JCM and JCM-west reference reaches.

5.2. Outcomes and Products

Project Element E.1.

Outcomes:

- We expect that this project element will constrain the potential importance of different P inputs to the canyon. The work will also identify the major forms of P in Colorado River sediments, the capacity for Colorado River sediments to take up P when water P concentrations are high, and the controls on sediment P uptake and release.

Products:

- Master's thesis and associated journal article on the Colorado River P budget.
- Journal article describing sediment P dynamics in Glen and Grand canyons.
- Journal article hindcasting patterns in P inputs to the Colorado River.

Project Element E.2.

Outcomes:

- We expect that this project element will further our understanding of the controls on riverine GPP and how controls change spatially throughout the canyon. We also expect to improve our understanding of how GPP and P relate to the most biologically available primary producer pool in Glen Canyon. We expect to gain a better understanding of the role of diatom vs. macrophyte communities in whole-river GPP. Additionally, we will set the base upon which to evaluate future changes in aquatic vegetation communities in Glen Canyon to measure long-term trends and/or the short-term effects of experimental flows on primary producers.

Products:

- Two journal articles identifying the most important controls on riverine GPP and describing how these controls vary spatially.
- One journal article describing results of our diatom experiment that examines interspecies effects on GPP, and the influence of mud snails on production.
- One journal article providing methodological details on using machine learning techniques in the context of aquatic vegetation surveys.

Project Element E.3.

Outcomes:

- We expect that this project element will provide a better understanding of the amount of energy needed for native fish growth. Ecosystem models will be developed that link primary production and changes in ecosystem drivers (temperature, flow, nutrients) to higher trophic levels across the CRe.

Products:

- One journal article that reports on the standard and active metabolic rates of humpback chub and flannelmouth sucker (i.e., inputs into the ecosystem model).
- One journal article describing correlations between GPP, invertebrate drift and fish condition/demography at various sites throughout the river.
- One journal article that introduces and describes the ecosystem model linking flow, temperature, nutrients, and energy needs to multiple trophic levels.

5.3. Personnel and Collaborations

A portion of the work described in Project E.1 will be conducted in collaboration with Robert Hall at the University of Montana as part of a Masters' student thesis project. In addition, the P analyses for this project element will be conducted at the University of Montana as part of the same Interagency Agreement.

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7. Budget

Fiscal Year 2021								
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
E.1. Phosphorus budgeting in the Colorado River	$67,797	$1,000	$5,000	$0	$81,500	$0	$12,777	**$168,074**
E.2. Rates and composition of primary producers in the Colorado River	$123,490	$7,400	$13,000	$6,400	$0	$0	$21,041	**$171,331**
E.3. Productivity at higher trophic levels (fish metabolism) - secondary production	$44,755	$0	$15,500	$0	$0	$0	$8,436	**$68,691**
Total Project E	**$236,042**	**$8,400**	**$33,500**	**$6,400**	**$81,500**	**$0**	**$42,253**	**$408,095**

Fiscal Year 2022								
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
E.1. Phosphorus budgeting in the Colorado River	$60,424	$1,000	$3,922	$0	$14,500	$0	$14,811	**$94,657**
E.2. Rates and composition of primary producers in the Colorado River	$89,758	$9,500	$10,000	$0	$0	$0	$24,037	**$133,294**
E.3. Productivity at higher trophic levels (fish metabolism) - secondary production	$54,025	$0	$0	$0	$0	$0	$11,886	**$65,911**
Total Project E	**$204,206**	**$10,500**	**$13,922**	**$0**	**$14,500**	**$0**	**$50,733**	**$293,862**

Fiscal Year 2023								
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
E.1. Phosphorus budgeting in the Colorado River	$70,536	$1,000	$3,500	$0	$0	$0	$21,010	**$96,046**
E.2. Rates and composition of primary producers in the Colorado River	$59,436	$7,000	$9,865	$0	$0	$0	$21,364	**$97,665**
E.3. Productivity at higher trophic levels (fish metabolism) - secondary production	$70,077	$2,500	$516	$0	$0	$0	$20,466	**$93,559**
Total Project E	**$200,049**	**$10,500**	**$13,881**	**$0**	**$0**	**$0**	**$62,840**	**$287,270**

8. Experimental Project Budget

Project Element E.4. Mapping Vegetation Response to Experimental Flows

Kimberly Dibble, Fish Biologist, USGS, GCMRC
Mike Yard, Fish Biologist, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC
Dan Buscombe, USGS, Western Ecological Research Center, Santa Cruz, CA
Robert Tusso, Hydrologist, USGS, GCMRC

A unique opportunity exists to apply a tool developed in the FY2015-17 and FY2018-20 workplans to answer research questions related to proposed experimental flows released from Glen Canyon Dam. In Project Element E.2, imagery analysis of thousands of underwater photos using machine learning techniques is allowing GCMRC scientists to understand the composition and cover of aquatic macrophytes in Glen Canyon at two established transects in the upper (~-13 RM) and lower (~-4 RM) sections of this reach of the Colorado River. This imagery is the first of its kind related to macrophyte composition and cover. It is anticipated that information gained from this project will serve as a baseline to answer questions related to the effects of dam operations on primary producers, whether that be long-term responses in the vegetation community, or short-term responses to disturbance effects such as HFEs, TMFs, and other proposed flows.

In spring 2021, a week-long steady 4,000 ft^3/s flow has been proposed for power plant/dam maintenance. This low, steady flow may be coupled with a subsequent power plant capacity flow (see related Project Element F.5). This could cause enough of a disturbance on the littoral edge to cause a change in macrophyte communities through both desiccation of edge habitat and scour/disturbance in deeper areas of the channel leading to macrophyte removal. As such, we propose to use this unique opportunity (coupled with advances to date in Project Element E.2) to understand how experimental flows impact the dominant primary producers in Glen Canyon, with a secondary objective of determining the scale at which we might be able to do so. This would be designed as a before and after-impact study, with one trip prior to the 4,000 ft^3/s flows, and two to three trips after the power plant capacity flows occur to detect vegetation response and recovery. If we can detect a change in percent vegetation cover and/or composition on a short-term scale (1 season), then that result informs the frequency at which we should undergo aquatic vegetation surveys. For example, if we can detect change within a season over multiple trips, this method could be considered a sensitive tool for detecting vegetation community responses to dam operations and would further our understanding of factors that drive primary production in Glen Canyon (Project E). This project is proposed to be funded by the Experimental Fund.

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

Funding for staff on Projects E.1 and E.2 was moved to the Interagency Lake Powell Water Quality Monitoring program, which will lead to us not hiring a new person to lead the Lake Powell work and tethers the sustainability of these elements to renewal of the Lake Powell agreement in FY2023. As a consequence, progress in understanding will necessarily move slower than initially planned as staff will balance multiple commitments. Furthermore, if funding for Lake Powell Water Quality Monitoring lapses, even temporarily, at the end of the current five year agreement in FY2022, we will be unable to maintain staff and complete work in these elements (in addition to losing essential data from Lake Powell including water quality in the forebay and our only long-term dataset regarding phosphorus). Funding to backfill a data scientist position jointly funded through the ecosystem modeling (proposed in E.3 of the current work plan) as well as salmonid modeling (Project H.4) was also eliminated. As a consequence, progress will be slower and our capacity to respond to unfunded modelling requests (e.g., LTEMP EIS, the brown trout EA, etc.) will be diminished.

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 primary 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) 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 (Figure 1). In May–August 2018–2020, Glen Canyon Dam operations were experimentally modified to try to increase the production and diversity of aquatic insects in the Colorado River ecosystem (CRe). 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. Project F is tracking ecosystem response to the Bug Flows experiment and other ongoing or potential management actions using citizen science monitoring of aquatic insects (F.1), monitoring of invertebrate drift (F.1 and F.2), monitoring of invertebrate communities in Bright Angel Creek in response to fisheries management actions (F.3), through diet and stable isotope analysis of fish feeding habits (F.4), and through monitoring and research associated with a potential, new spring flow disturbance (F.5).

Research and monitoring of invertebrates described in Project F also provides essential context and data that are used by other projects. For example, invertebrate monitoring data are used by Project E (Controls on ecosystem productivity) to identify the extent to which changing nutrient levels are propagating up through the food web. Invertebrate monitoring data also aid interpretation of seasonal and annual trends in humpback chub (Project G) and rainbow trout (Project H), because aquatic invertebrates represent the food base for both species of fish. Project F also integrates and uses data from other projects, particularly Project A (Streamflow, water quality, and sediment transport), to identify how changing environmental conditions affect invertebrate populations.

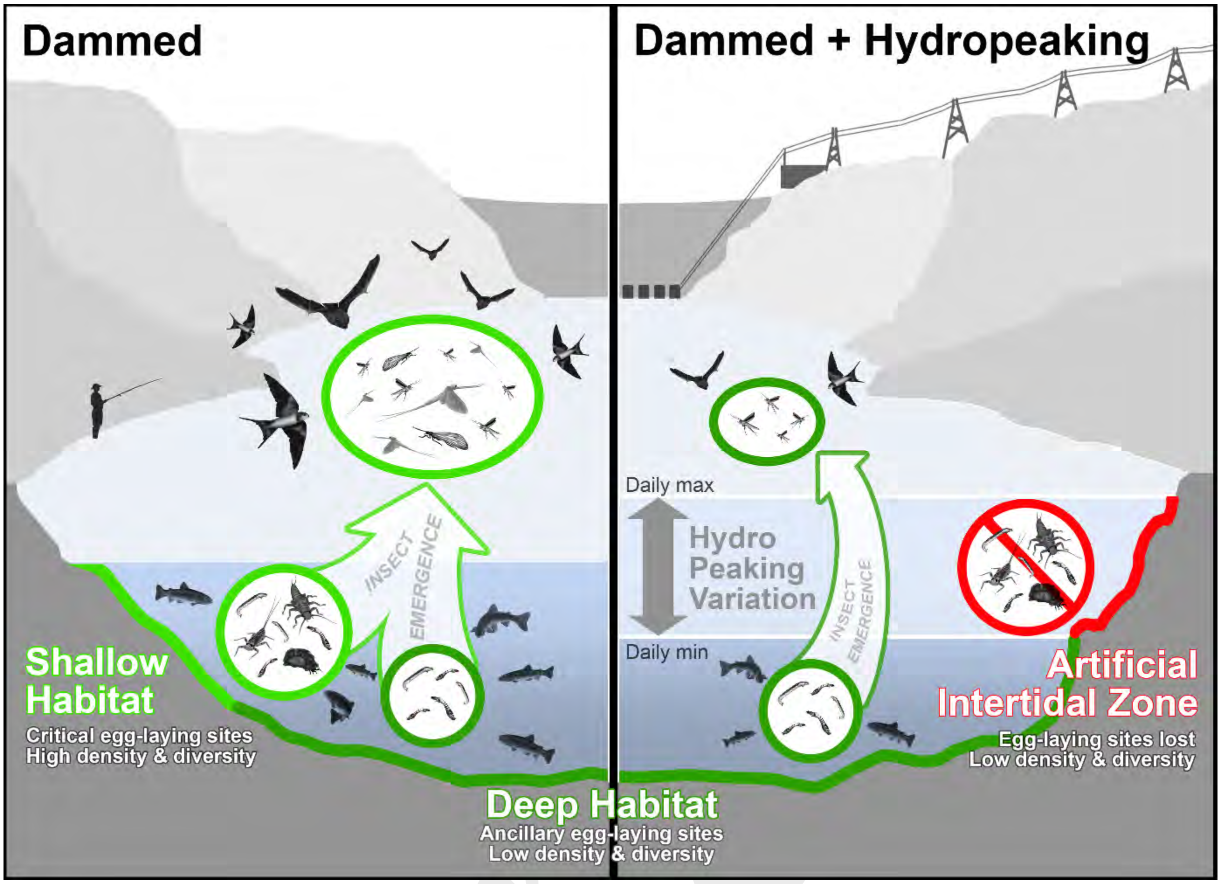

Figure 1. Conceptual model highlighting the essential role that aquatic insects play in river food webs. Ecologically important insect groups such as mayflies, stoneflies, and caddisflies cement their eggs along river-edge habitats, making them especially sensitive to hydropower production practices that affect these edge habitats. The Bug Flow experiment seeks to mitigate these negative impacts by periodically providing favorable egg laying conditions for aquatic insects, which is expected to shift food webs to look more like the left side of this diagram.

3. Hypotheses and Science Questions

Our ability to test hypotheses and answer science questions concerning the food base will depend in part on which flow experiments occur during FY2021-23. Testing of experimental Bug Flows in 2018-2020 has already provided a wealth of data, which will be used to test management-relevant hypotheses including:

- H1: Macroinvertebrate production flows increase the abundance of midges in the CRe by increasing improving survival of sensitive insect eggs (Figures 1, 2).
- H2: Macroinvertebrate production flows increase the abundance of EPT (Ephemeroptera, Plecoptera, Trichoptera) in the CRe by improving survival of sensitive insect eggs (Figures 1, 2).

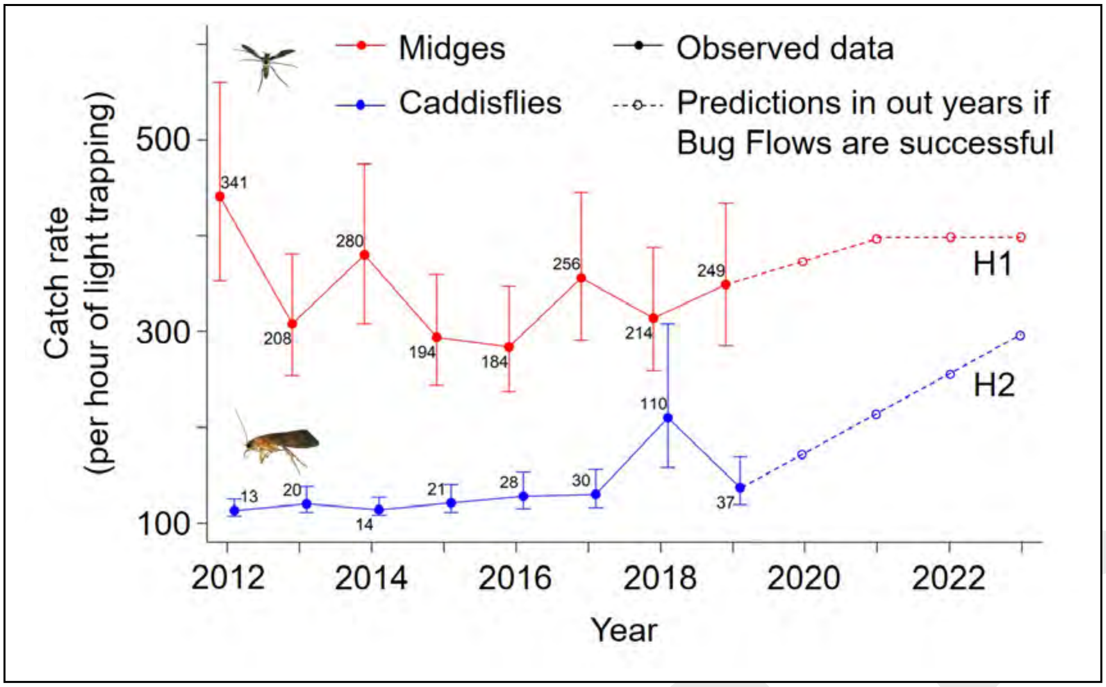

Figure 2. Citizen science light trap catches of midges and caddisflies by year (solid lines and circles) and predicted future catch rates (H1 and H2) based on Bug Flows modeling (dashed lines and circles).

Bug Flows has been approved for FY2020 and is currently being implemented. However, given uncertainties with monitoring Bug Flows in 2020 owing to the COVID-19 pandemic and the closure of the Colorado River through Grand Canyon to all river trips in spring 2020, our ability to definitively test H1 and H2 would be improved substantially by additional years of Bug Flows testing and monitoring.

Additionally, for the first time as part of LTEMP, spring high flow experiments (HFEs) are possible during the next three years if sediment triggers are reached. Spring HFEs and other types of spring flow disturbances are also hypothesized to increase the abundance of aquatic insects, but via different mechanisms than Bug Flows. Conducting a spring flow disturbance will allow testing of hypotheses such as:

- H3: Fall flow disturbances scour the river bottom at the end of the growing season, causing short-term reductions in algae and invertebrate abundance that eventually recover to baseline values (Figure 3).
- H4: Spring flow disturbances scour the river bottom just before the start of the growing season, causing reductions in algae and invertebrates, but the new community of algae is of higher quality, more productive, and is assimilated more efficiently by invertebrates, thereby increasing invertebrate abundance over the long-term (Figure 3).

Adaptive management experimentation during FY2021-23 could also involve testing both Bug Flows and a spring disturbance simultaneously. Bug Flows are designed to improve survival of insect eggs while flow disturbances in spring are hypothesized to improve growing conditions for insect larvae. Thus, testing these two experimental flows in the same year could have positive and synergistic effects on aquatic insects that are much greater than either experiment alone.

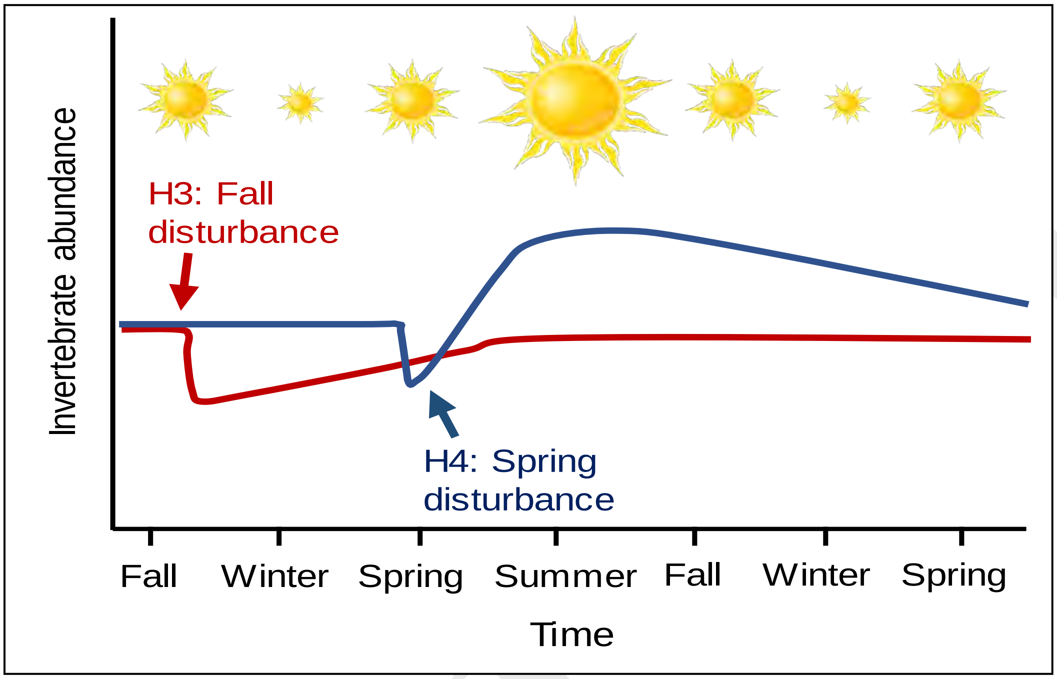

Figure 3. Hypothetical invertebrate community responses to the seasonal timing of flow disturbances (i.e., very low and/or very high flows that cause disturbance by desiccating or scouring the river bottom). Under H3, flow disturbances in fall cause an immediate reduction in invertebrate abundance, which gradually recovers to pre-disturbance levels. Under H4, flow disturbance in spring causes an immediate reduction in abundance, but the algae and invertebrate community quickly rebounds and even exceeds it pre-disturbance abundance levels, See main text for further detail.

4. Background

Project F supports adaptive ecosystem management by addressing important LTEMP goals and other information needs. A productive and diverse aquatic food base is an indicator of healthy *Natural Processes*. Thus, Project F aligns with the associated LTEMP goal by identifying how to:

> *Restore, to the extent practicable, ecological patterns and processes within their range of natural variability, including the natural abundance, diversity, and genetic and ecological integrity of the plant and animal species native to those ecosystems.*

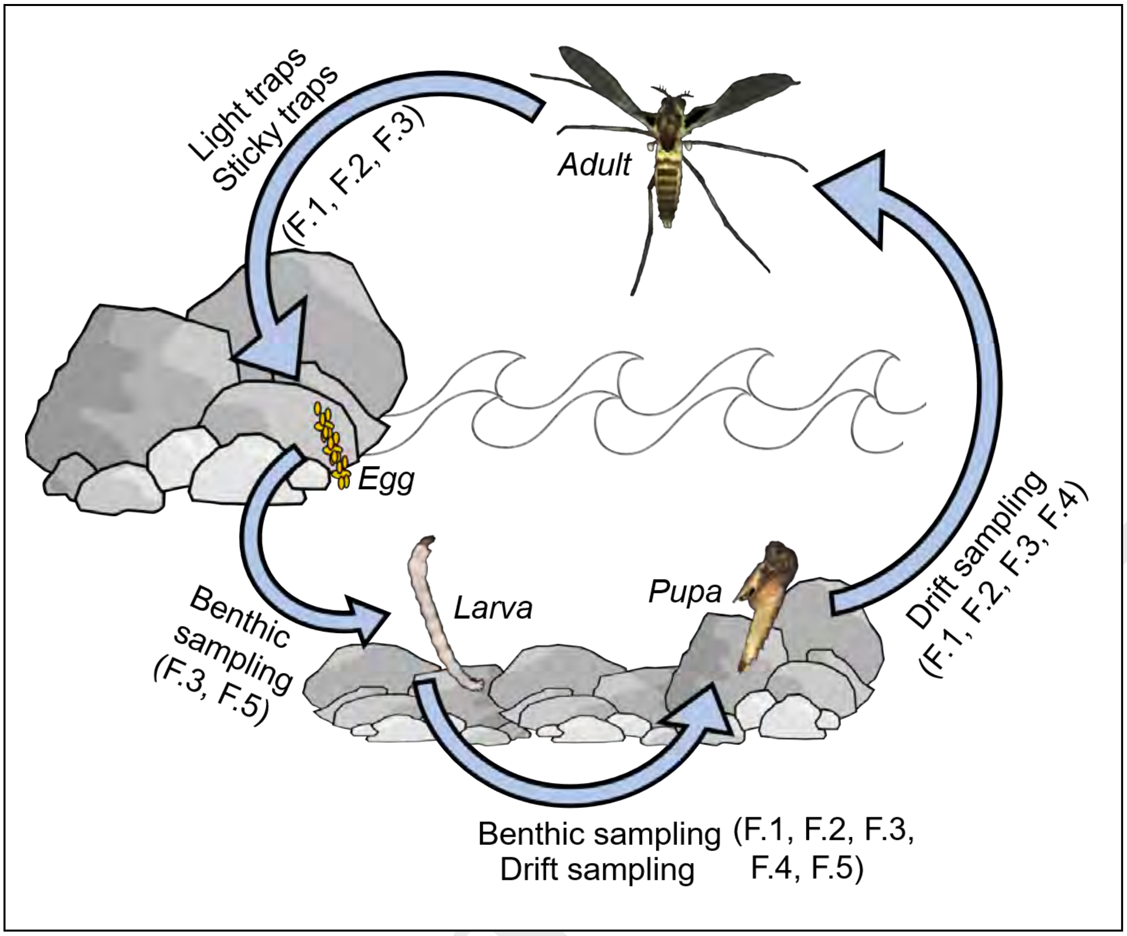

Figure 4. Typical life cycle of an aquatic insect. Non-biting midges (Chironomidae), which represent the dominant aquatic insect in the Colorado River food web, are shown. The diversity of sampling methods utilized in Project F target different life stages of insects. Aquatic insects are susceptible to fish predation at all life stages, but especially during the drifting life stage just prior to adult emergence. Research by Project F has shown that fluctuating flows associated with hydropower generation cause mortality at the egg stage, disrupting insect life cycles. The Bug Flow experiment seeks to restore the *Natural Processes* that sustain aquatic insects and food webs by periodically providing stable flows that enhance egg survival.

The U.S. Fish and Wildlife Service identified the lack of an adequate and reliable food base as the single greatest threat to humpback chub in Grand Canyon (USFWS, 2018). Project F informs these recovery efforts and LTEMP goals for humpback chub, rainbow trout, and other native fish by identifying cost-effective strategies for improving the aquatic food base and tracking food base response to ongoing adaptive management experimentation (Figures 4, 5). Project F also supports 2016 humpback chub Biological Opinion Conservation Measures (USFWS, 2016) by monitoring invertebrate communities in Bright Angel Creek where humpback chub translocations are ongoing.

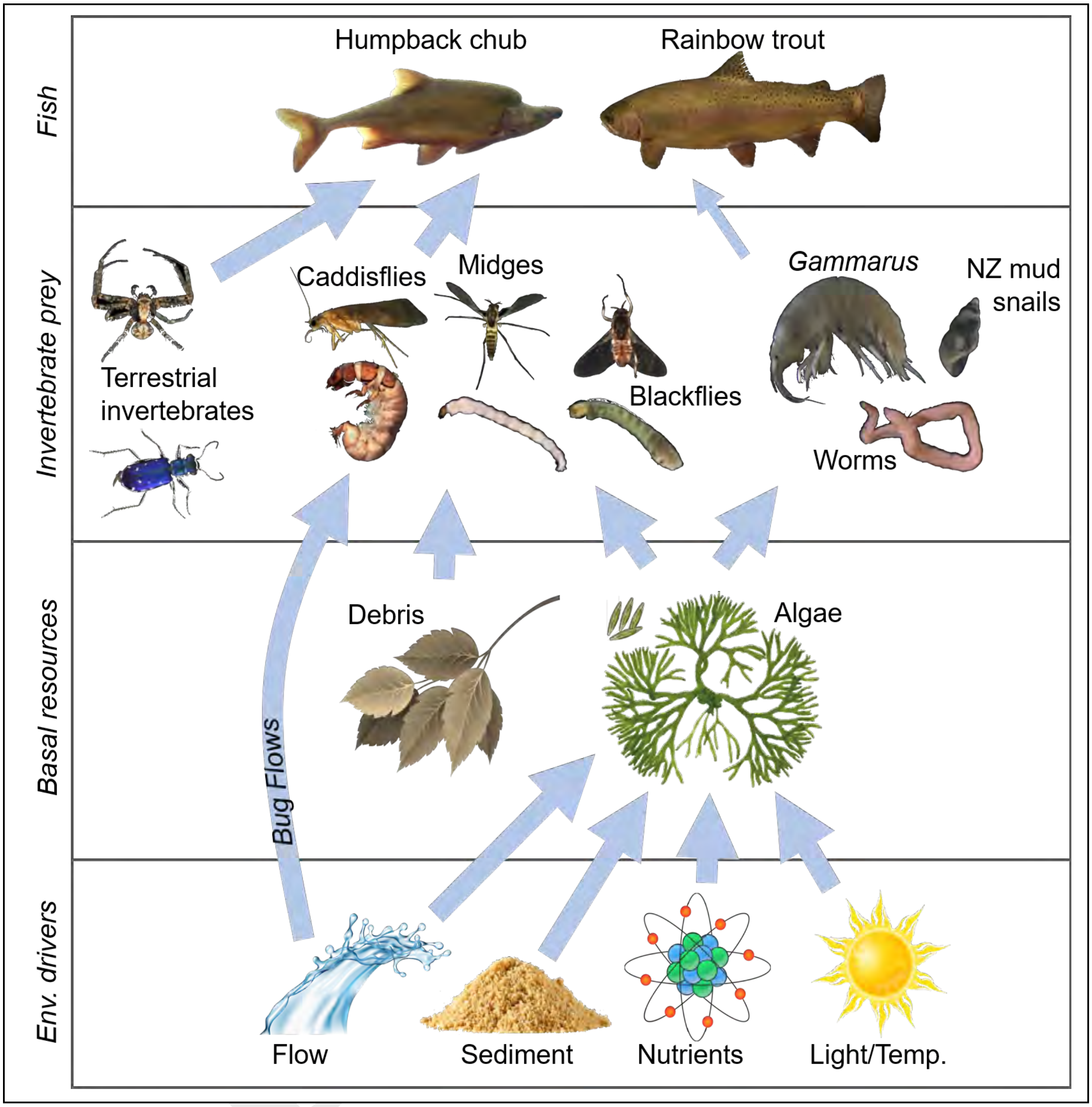

Figure 5. Conceptual model of the Colorado River ecosystem. Arrows indicate linkages between food web components, with the strength of the arrow roughly indicating the strength of the linkage. Note the arrow between flow and aquatic insects, which is the linkage being tested by the Bug Flows experiment.

5. Proposed Work

5.1. Project Elements

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

Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Morgan Ford, Ecologist and Lab Manager, USGS, GCMRC
Charles Yackulic, Research Statistician, USGS, GCMRC

Aquatic invertebrates exhibit movements and behaviors that are ecologically important, not only because these processes are critical to invertebrate life cycles and population dynamics, but because these movements make invertebrates vulnerable to predation by wildlife populations. For instance, although most stream invertebrates are benthic (bottom dwelling), invertebrates are also regularly found drifting with the river current. This process of drift is essential to invertebrate dispersal and colonization and therefore critical to population maintenance of these animals (Brittain and Eikeland, 1988). Similarly, of the many insect stream invertebrates, nearly all transition to becoming winged, air-breathing adults via emergence (Figure 4). Each of these are critical stages in invertebrate life cycles (Huryn and Wallace, 2000), but also processes by which they become vulnerable to fishes and terrestrial food webs, often serving as prey for animals like birds, bats, spiders and lizards (Baxter and others, 2005). Increasingly, conditions necessary to support insects not just at the larval stage, but throughout their life cycles (e.g., egg, larvae, pupae, adult) are understood to be important to species management and recovery efforts (Kennedy and others, 2016).

This project element focuses on identifying links between Glen Canyon Dam operations and the downstream aquatic food base. We focus our efforts on monitoring invertebrate populations during periods of movement (i.e., emergence and drift), because these drift and emergence data can be used to make inferences about the health and status of invertebrate populations (Kennedy and others, 2014; Kennedy and others, 2016) and also provide a direct measure of the food base available to humpback chub, rainbow trout, and other wildlife populations (see Projects G and H, especially). The core monitoring described in this project represents the principal data collection effort by which GCMRC will evaluate the efficacy of Bug Flows, HFEs, and any other experimental changes to dam operations intended to improve the aquatic food base. If such flow experiments are not implemented, these monitoring efforts still represent an important, long-term dataset that allows us to characterize the status and trends of the aquatic food base and identify the role of environmental variation in affecting the food base (Figures 2, 5).

The main thrust of F.1 is the citizen science monitoring of emergent aquatic insects, where river guides, education groups, private boaters, and other citizen scientists deploy a simple light trap each night in camp to collect samples of adult aquatic insects that have emerged from the Colorado River. This citizen science monitoring has been ongoing since 2012 and is an important line of evidence for evaluating the effectiveness of Bug Flows. Multiple monitoring metrics including light trapping indicated a strong and positive food base response to the first year of Bug Flows testing in 2018, followed by a decline back to baseline values in 2019 (Figure 2). However, interpretation of these Bug Flows data is complicated by a large increase in tributary flooding in winter-spring of 2019 relative to all prior years (2012-18); high levels of suspended sediment from tributaries are a major constraint on growth and production of aquatic insects (Glen Canyon Technical Team, 2020). Additional years of Bug Flows testing and citizen science monitoring in FY2021-23 would be useful in quantifying the extent to which these experimental flows increase the abundance and diversity of the food base in Glen and Grand Canyon.

Laboratory processing of citizen science light trap samples includes counting and identifying aquatic insects to family or genus, whereas terrestrial insects are identified to order or family. For around 20% of samples, aquatic insect specimens are archived at GCMRC. In January 2017, GCMRC established a memorandum of understanding with Museum of Northern Arizona (MNA) and Grand Canyon National Park that allows the transfer of terrestrial insect specimens to MNA for identification and archiving. MNA is providing this service at no cost.

Finally, as part of F.1, we will also monitor invertebrate drift (#/m^3 and g/m^3) in the Colorado River throughout Marble and Grand Canyons during annual river trips in spring. As part of these annual monitoring trips, which began in 2017 prior to the first Bug Flows experiment, invertebrate drift samples will be collected approximately every 3 river miles. This type of strategic monitoring of drift throughout Marble and Grand Canyon complements more spatially and temporally extensive citizen science monitoring by providing an independent line of evidence for evaluating food base response to Bug Flows and other LTEMP flow experiments.

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

Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Morgan Ford, Ecologist and Lab Manager, USGS, GCMRC
Bridget Deemer, Research Ecologist, USGS, GCMRC

This element is a continuation of monthly Glen Canyon monitoring program that has been ongoing since 2007. It represents a valuable long-term dataset for identifying status and trends in the aquatic food base supporting rainbow trout populations in Glen Canyon. Further, regular sampling in Glen Canyon is an effective proxy for understanding food base conditions downstream in Marble and Grand Canyons, where sampling is logistically much more expensive and difficult. This is especially the case during times of year (such as fall, winter, and early spring), when the citizen science light trapping described in F.1 becomes rare. Collectively, near-monthly sampling in Glen Canyon therefore provides us the only effective means of monitoring the aquatic food base of the CRe year-round (Figure 6). This monitoring is carried out using published methods developed by the food base group (Copp and others, 2014; Kennedy and others, 2014; Smith and others, 2014; Baxter and others, 2017; Muehlbauer and others, 2017). With the benefit of learning from these past years, in this work plan we will also be able to reduce sampling to every other month in the winter when aquatic insect activity is predictably lower and less variable from month-to-month. This reduces field work and processing costs associated with this monitoring by ~15%.

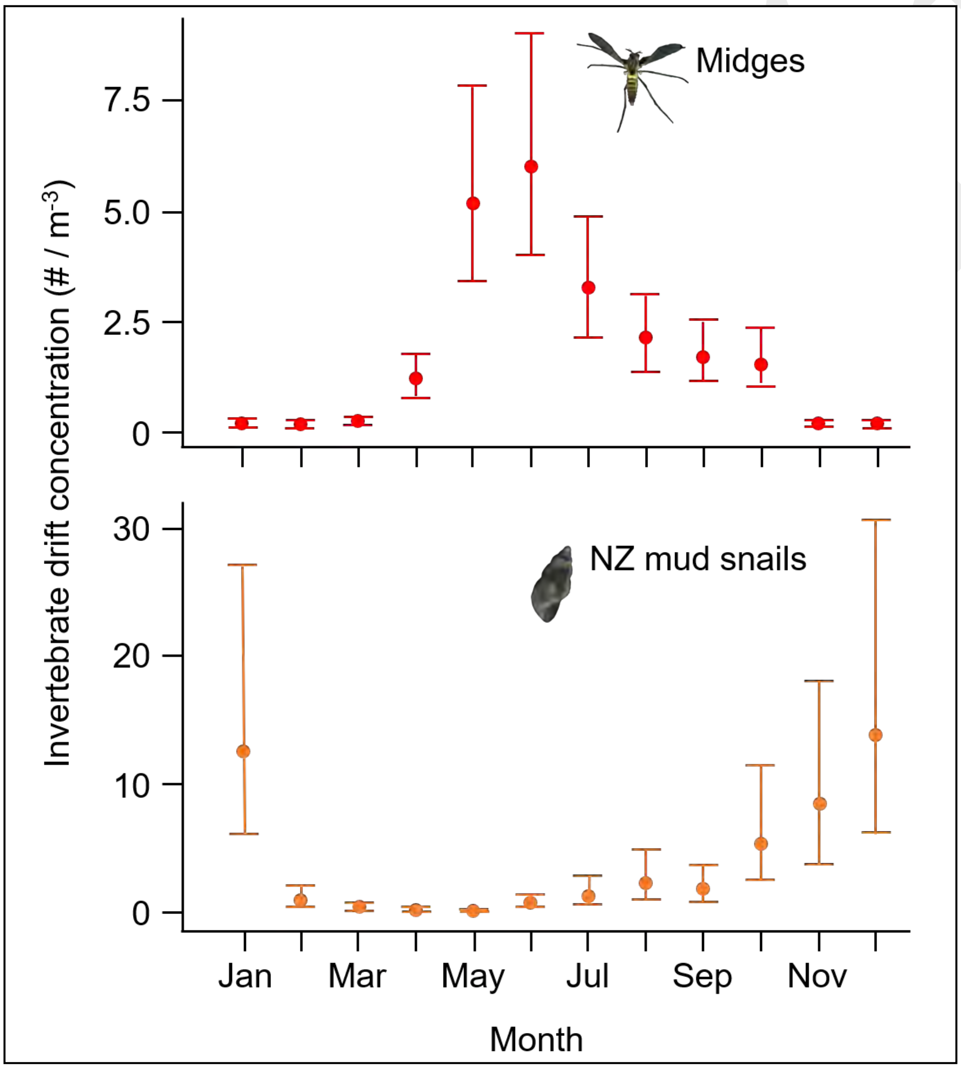

Figure 6. Drift concentrations of midges and New Zealand mud snails from Glen Canyon monthly monitoring. Note the seasonal differences, with more midge activity in summer months and more mud snail activity in the winter. Midges are hypothesized to benefit from spring high flow experiments (HFEs), because these disturbances occur prior to midge peak activity in summer. Similarly, November HFEs are thought to benefit New Zealand mud snail populations, because they occur immediately prior to peak activity in winter.

Invertebrate drift will be sampled ten times per year at eight sites distributed from Glen Canyon Dam (River Mile -16) to the head of Badger Rapid (River Mile 8). This dataset allows us to understand and model changes in invertebrate drift over time and in response to flow conditions such as riffles, pools, and tributary sediment inputs from the Paria River (Figure 5). Because rainbow trout and humpback chub are both predominantly drift-feeding fish, these data provide a direct measure of the food most available to these fishes. Drift data are also more tightly correlated to larval aquatic insects on the bed of the river, "the benthos" (Statzner and Resh, 1993; Figure 4); as such, these data provide a useful metric in comparing conditions in the CRe to other streams and rivers that are monitored using more traditional benthic sampling. Such benthic sampling is generally infeasible in the CRe due to safety concerns (but see F.5 for a unique opportunity to potentially collect these data in FY2021).

Adult aquatic insects are also monitored during these monthly sampling trips using sticky and light traps. These paired datasets allow us to more directly compare data from Glen Canyon sampling with the citizen science light trapping effort throughout Marble and Grand Canyons described in F.1. Because traps are placed at the same locations on every sampling trip, sticky trap data also provide a robust metric for assessing monthly changes in adult aquatic insect activity, particularly in response to ecosystems changes such as those hypothesized to occur during the Bug Flows experiment.

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

Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Anya Metcalfe, Ecologist, USGS, GCMRC

This element involves monitoring the aquatic invertebrate community within Bright Angel Creek in Grand Canyon. This creek represents a site of recent and ongoing nonnative trout removals, which in the last year has also been coupled with humpback chub translocations. For this reason, understanding the extent of aquatic food base resources available to fish in the creek can influence decisions about whether to translocate more fish or scale back trout removals, and in evaluating the potential success of the translocations. Changes to the food base in these streams may also provide an early indicator of potentially detrimental conditions for fish populations already in the creek.

In cooperation with the National Park Service (NPS), we will continue monitoring the aquatic food base in Bright Angel Creek in FY2021. This data collection started in 2013 prior to nonnative trout removal efforts (Whiting and others, 2014). 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 (Daubert and others, 2017). Sampling consists predominantly of traditional benthic sampling at sites near the confluence of the creek with the mainstem, 800 m upstream (adjacent to Phantom

Ranch), and 3200 m upstream of the confluence. Sticky traps are deployed at these sites as well, and light traps are collected at the Phantom Ranch site. Consistent with pre-trout removal data collection, drift is collected in the morning, midday, and evening at the Phantom Ranch site as well (Whiting and others, 2014). This sampling occurs roughly quarterly in January, June, September, and November, based on the sampling regime established in that pre-trout removal study.

Continuing sampling in Bright Angel Creek into FY2021 is likely to be particularly important, with the proposed translocation of 400 humpback chub into the creek in the summer of 2020. However, in the interest of efficiently utilizing budgetary resources, this project will be discontinued in FY2022 since any aquatic invertebrate community response to these fisheries activities will most likely have stabilized by that time. In addition to invertebrate sampling in the creek, we will also collect fin clips from fishes for stable isotope analysis or collect fish gut contents using non-lethal lavage methods (Stone, 2004). These data will allow us to more directly link native fish feeding within the creek to the aquatic invertebrate community, and to determine the extent to which these invertebrates are critical to the persistence of these fishes in the creek. This analysis will occur pending the availability of native fish captured during NPS monitoring efforts.

Project Element F.4. Fish Diet Studies

Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Kimberly Dibble, Fish Biologist, USGS, GCMRC

Current food base monitoring approaches were informed by detailed food web studies and fish diet analysis of samples collected from 2006–2009 (Cross and others, 2013; Kennedy and others, 2013). These studies identified that algae fuels growth of invertebrate populations everywhere, even at muddy downstream sites where algae are scarce (Wellard Kelly and others, 2013). Based on these insights, GCMRC scientists and collaborators developed techniques for continuously monitoring the algae-portion of the food base using dissolved oxygen budgeting (see Project E), which has shed light on the role of dam operations and environmental factors in regulating algae growth (Hall and others, 2015).

Early diet studies also identified that aquatic insects were key prey for native and desired nonnative fishes (Cross and others, 2013; Zahn Seegert and others, 2014), but the low production and diversity of aquatic insects in the CRe appeared to be a major constraint on fish populations overall (Kennedy and others, 2013). Thus, GCMRC scientists developed new techniques for studying the invertebrate-portion of the food base, including citizen science light trapping of the understudied adult life stage of aquatic insects (Kennedy and others, 2016); insights from these new studies informed the design of Bug Flows and have provided a powerful and low-cost approach for monitoring.

Finally, food web studies from 2006–2009 also demonstrated that nonnative New Zealand mud snails consumed a huge proportion of the available algae energy in Lees Ferry (Cross and others, 2010), but they were inedible to rainbow trout and represented a "trophic dead-end."

Food webs throughout the CRe have experienced major changes in the decade since these studies were conducted, and these food web changes may have affected fish feeding habits and the food base that is available to fish (Figure 7). For example, the invasion of quagga mussel to the CRe starting around 2013 might represent the addition of another trophic dead-end, similar to New Zealand mud snails. A decade ago, the feeding habits of humpback chub could only be assessed at the LCR confluence, where these endangered fish were relatively common. Now, in 2020, humpback chub are also common far downstream in western Grand Canyon, but the ecological mechanism driving this population expansion remains unclear (see Project G). Increases in nonnative brown trout in Lees Ferry and flannelmouth sucker increases systemwide might also have an underlying food web cause.

This project element will re-assess feeding habits of key fish species to inform ongoing fishery investigations and determine whether food base monitoring approaches need updating. Specifically, in 2021 and 2022 we will synthesize rainbow and brown trout diet data collected from 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. For one year (FY2022) we will seasonally collect diet samples of native fish species (i.e., humpback chub, flannelmouth sucker, bluehead sucker, and speckled dace) at the LCR confluence and Fall Canyon to determine the extent to which native fish are utilizing caddisflies, quagga mussels, or other newly available invertebrate prey in their diets. Non-lethal fish lavage methods (Stone, 2004) will be utilized to the extent practical in collecting these samples.

As part of this re-analysis, we will also collect fin clips from native fish for stable isotope analysis. Carbon and nitrogen stable isotope analysis of fin clips provide a non-lethal indication of long-term feeding habits including the trophic position of the fish and the relative importance of algae vs. terrestrial detritus to fish production overall. This long-term information on general feeding habits obtained from stable isotopes complements the detailed "snapshot" of feeding habits from diet analysis. Synthesis of downstream food webs and diet information will occur in the final year of the workplan (FY2023). Importantly, this synthesis will include comparing feeding habits of humpback chub at the LCR confluence with the western Grand Canyon population, which will help fishery scientists identify potential mechanisms underlying this population expansion. Combined, the monitoring and research described in F.4 will elucidate the extent to which Bug Flows may be affecting the food base available to rainbow trout and native fishes and will help scientist identify causes of recent native fish population increases in western Grand Canyon.

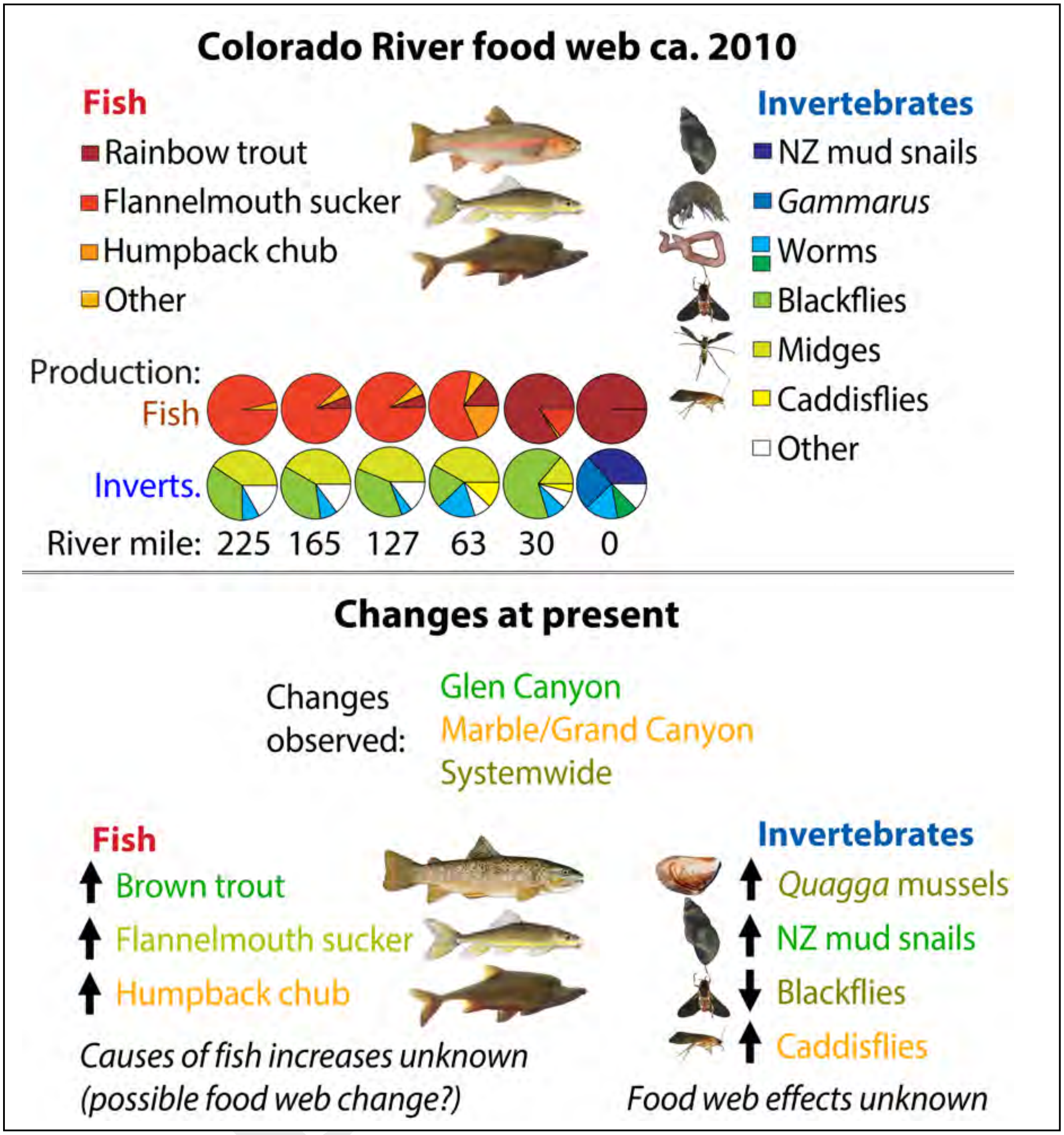

Figure 7. Food webs in the Colorado River ecosystem. The top panel shows ecosystem food web production, based on studies from 2006–2009 (Cross and others, 2013; Kennedy and others, 2013), and bottom panel highlights known changes to food web components in the decade since. The effects of these changes on the food web, and the extent to which changes in the aquatic invertebrate community may be affecting observed changes in the fish community, are currently unknown and represent the focus of F.4.

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

Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Daren Carlisle, Eco-Flows Program Manager, USGS, Water Mission Area
David Lytle, Professor, Oregon State University, Department of Integrative Biology
Scott Wright, Research Hydrologist, USGS-California Water Science Center

This Experimental Fund element focuses on quantifying food base response to springtime flows being considered by the Flow Ad Hoc 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 mud snails. 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, the five fall HFEs tested from 2012-present 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 mud snails. Furthermore, a recent synthesis of flow and invertebrate data from streams and rivers throughout the nation found that spring high flows are one of the most important factors contributing to diverse and productive aquatic insect assemblages (Carlisle and others, 2017). Analysis of Paria River discharge data indicate sediment-triggered spring HFEs are increasingly unlikely owing to decadal-scale 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.

5.2. Outcomes and Products

Project F will evaluate food web response to macroinvertebrate production flows, HFEs, and other LTEMP flow experiments. Each of the five project elements will result in one or more peer-reviewed journal articles and presentations at scientific meetings (Table 1). These project elements describe cutting-edge work in applied aquatic ecology, and the outcome of several of these project elements will be the publication of papers in the highest-tier scientific journals. We will also provide summaries of key food base monitoring metrics (e.g., light trap catches, EPT abundance, long-term drift in Lees Ferry) at the GCDAMP Annual Reporting Meeting held each January. Additionally, we can provide more frequent summaries of key monitoring metrics, contingent upon sample processing progress, if there is interest in evaluating the initial food base response to any LTEMP flow experiments.

Table 1. Potential products resulting from Project F in the FY2021-2023 work plan.

Potential product title	Proposed outlet
F.1 (Marble/Grand Canyon monitoring)	
Ecosystem responses to the Bug Flows experiment at Glen Canyon Dam	Journal (*Science*)
Ecosystem responses to the Bug Flows experiment at Glen Canyon Dam	Conference (*Ecological Society of America*)
Suspended sediment, flow, and other environmental conditions as a driver of aquatic insect emergence	Journal (*Freshwater Biology*)
Suspended sediment, flow, and other environmental conditions as a driver of aquatic insect emergence	Conference (*Society for Freshwater Science*)
F.2 (Glen Canyon monitoring)	
Spatial and temporal drivers of invertebrate drift in the tailwater of a large dam	Journal (*Freshwater Biology*)
Spatial and temporal drivers of invertebrate drift in the tailwater of a large dam	Conference (*Ecological Society of America*)
Aquatic invertebrate community responses to a series of high flow experiments at Glen Canyon Dam	Journal (*BioScience*)
Aquatic invertebrate community responses to a series of high flow experiments at Glen Canyon Dam	Conference (*Ecological Society of America*)
F.3 (Tributary invertebrate research)	
Trout removal in an arid stream initiates a trophic cascade	Journal (*Freshwater Science*)
Potential for food limitation in translocated fish in Havasu Creek based on invertebrate abundance	Report (*USGS Open File Report*)
Long-term trends in aquatic invertebrate diversity in the Colorado River in Grand Canyon	Journal (*Canadian J. Fisheries and Aquatic Sci.*)
Long-term trends in aquatic invertebrate diversity in the Colorado River in Grand Canyon	Conference (*Society for Freshwater Science*)
F.4 (Native and nonnative fish diets)	
Do steady, low flows affect rainbow trout feeding?	Journal (*Fisheries*)
Do steady, low flows affect rainbow trout feeding?	Conference (*American Fisheries Society*)
Differential feeding strategies between rainbow and brown trout in a large dam tailwater	Journal (*Canadian J. Fisheries and Aquatic Sci.*)
Aquatic invertebrate community change in western Grand Canyon as a driver of native fish increases	Journal (*Ecological Applications*)
Aquatic invertebrate community change in western Grand Canyon as a driver of native fish increases	Conference (*Ecological Society of America*)
Can any native or nonnative Colorado River fish ingest nonnative mud snails and mussels?	Conference (*Desert Fishes Council*)
F.5 (Experimental Fund, spring disturbance)	
Role of spring vs. fall flow disturbances in structuring aquatic invertebrate communities	Journal (*Ecology*)
Role of spring vs. fall flow disturbances in structuring aquatic invertebrate communities	Conference (*Ecological Society of America*)
Substrate manipulation and flow disturbance as a lever on non-native gastropod control	Conference (*Society for Freshwater Science*)
Long-term change in aquatic invertebrate community structure in the Colorado River in Grand Canyon	Journal (*Freshwater Biology*)

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7. Budget

Fiscal Year 2021								
Project F Aquatic Invertebrate Ecology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							14.00%	
F.1. Aquatic invertebrate monitoring in Marble and Grand Canyons	$257,778	$3,000	$28,000	$16,386	$0	$0	$42,723	**$347,888**
F.2. Aquatic invertebrate monitoring in Glen Canyon	$202,842	$12,503	$8,000	$7,500	$0	$0	$32,318	**$263,164**
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$79,833	$5,702	$1,000	$0	$0	$0	$12,115	**$98,649**
F.4. Diets of native and nonnative Colorado River fishes	$48,807	$0	$1,000	$0	$0	$0	$6,973	**$56,780**
Total Project F	**$589,260**	**$21,205**	**$38,000**	**$23,886**	**$0**	**$0**	**$94,129**	**$766,480**

Fiscal Year 2022								
Project F Aquatic Invertebrate Ecology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							22.00%	
F.1. Aquatic invertebrate monitoring in Marble and Grand Canyons	$243,160	$3,390	$28,540	$16,964	$0	$0	$64,252	**$356,306**
F.2. Aquatic invertebrate monitoring in Glen Canyon	$193,171	$12,869	$8,240	$7,500	$0	$0	$48,792	**$270,572**
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$0	$0	$0	$0	$0	$0	$0	**$0**
F.4. Diets of native and nonnative Colorado River fishes	$65,225	$1,393	$1,030	$0	$0	$0	$14,883	**$82,531**
Total Project F	**$501,556**	**$17,653**	**$37,810**	**$24,464**	**$0**	**$0**	**$127,926**	**$709,409**

Fiscal Year 2023								
Project F Aquatic Invertebrate Ecology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
F.1. Aquatic invertebrate monitoring in Marble and Grand Canyons	$235,165	$3,792	$29,096	$17,542	$0	$0	$79,967	**$365,562**
F.2. Aquatic invertebrate monitoring in Glen Canyon	$185,876	$13,247	$8,487	$7,500	$0	$0	$60,231	**$275,341**
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$0	$0	$0	$0	$0	$0	$0	**$0**
F.4. Diets of native and nonnative Colorado River fishes	$46,002	$0	$0	$0	$0	$0	$12,881	**$58,883**
Total Project F	**$467,043**	**$17,039**	**$37,583**	**$25,042**	**$0**	**$0**	**$153,078**	**$699,786**

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

See budget table in Experimental Project Fund Appendices.

7. Elements and Activities Proposed, but not funded in the Work Plan

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

Jeffrey D. Muehlbauer, Research Ecologist, USGS, GCMRC
Theodore A. Kennedy, Research Ecologist, USGS, GCMRC
Anya Metcalfe, Ecologist, USGS, GCMRC

Due to budget reductions, much of the work proposed in Project Element F.3 was not funded in the Work Plan. First, we had proposed to continue Bright Angel Creek invertebrate monitoring through FY2022, rather than ceasing this monitoring in FY2021 (see the funded portion of Project F.3, above).

Second, in FY2021-23 we had proposed to collect benthic invertebrate samples in Havasu Creek, another CRe tributary where humpback chub translocation has occurred and where a population is now resident. The objective of this sampling was to quantify the extent of perceived food limitation for these fishes (B. Healy, NPS, pers. comm.). Sampling would have occurred in collaboration with NPS staff during their May and September Havasu Creek fish sampling trips and would have consisted of replicated benthic samples similar to those collected in Bright Angel Creek (Whiting and others, 2014). These samples would have allowed us to provide a coarse and low-cost estimate of secondary production (invertebrate biomass) in Havasu Creek, and thus the amount of food available for a given population size of humpback chub. We would also have leveraged existing, ad-hoc samples collected in prior years by NPS personnel to establish the extent of annual change in food base condition in the creek and identify any longer-term trajectories in this food base.

Third, we had proposed to complete a synoptic survey of all major and minor perennial tributaries in the CRe. The goal of this research was to provide a baseline for the aquatic invertebrate community throughout the CRe. Similar sampling occurred in the 1990s (Oberlin and others, 1999) and in 2014 by GCMRC. During FY2021-23 we would have completely processed and published these 2014 samples, which were collected ad hoc as opportunity allowed and stored for future processing. This information would have be useful in tracking long-term changes in aquatic invertebrate diversity throughout the CRe.

Critically, it would also provide the only current information on whether CRe tributaries harbor enough insect diversity to potentially re-colonize the mainstem Colorado River in Grand Canyon if the Bug Flows experiment is successful, or whether geographic isolation is so severe that repatriation of native mayflies, stoneflies, and caddisflies from other segments of the Colorado River might be warranted. Consistent with the *New Actions* identified in the 2016 Biological Opinion (USFWS, 2016), this project would have also identified tributaries with high invertebrate biomass and diversity that would be logical choices for future native fish reintroductions.

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

1. Investigators

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

2. Project Summary

During FY2021-23, we will continue some, but not all, monitoring activities mandated by the 2016 Biological Opinion (BiOp; USFWS, 2016) associated with the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS; U.S. Department of the Interior, 2016), while focusing research on improving our understanding of abundance and the drivers of humpback chub population dynamics throughout the lower Colorado River ecosystem (CRe). Intensive sampling associated with this project focuses on humpback chub that spawn in the Little Colorado River (LCR) as well as individuals in western Grand Canyon, however mark-recapture research in western Grand Canyon will cease in FY2023, which will make it unlikely that we will determine drivers of chub dynamics there, potentially failing to meet a conservation measure.

The LCR-spawning portion of the population has been a stronghold for humpback chub since emplacement of Glen Canyon Dam in the 1960s. This portion of the population experienced a decline in the late 1990s and early 2000s but has been stable or increasing ever since then (Coggins and others, 2006; Van Haverbeke and others, 2013; Yackulic and others, 2018). However, monitoring of juvenile fish indicates the LCR-spawning portion of the population has displayed decreased juvenile production since 2012. As a result, we expect adult abundance to decline in the near term; however, the magnitude of this decline is less certain (Figure 1).

During FY2021-23, 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.

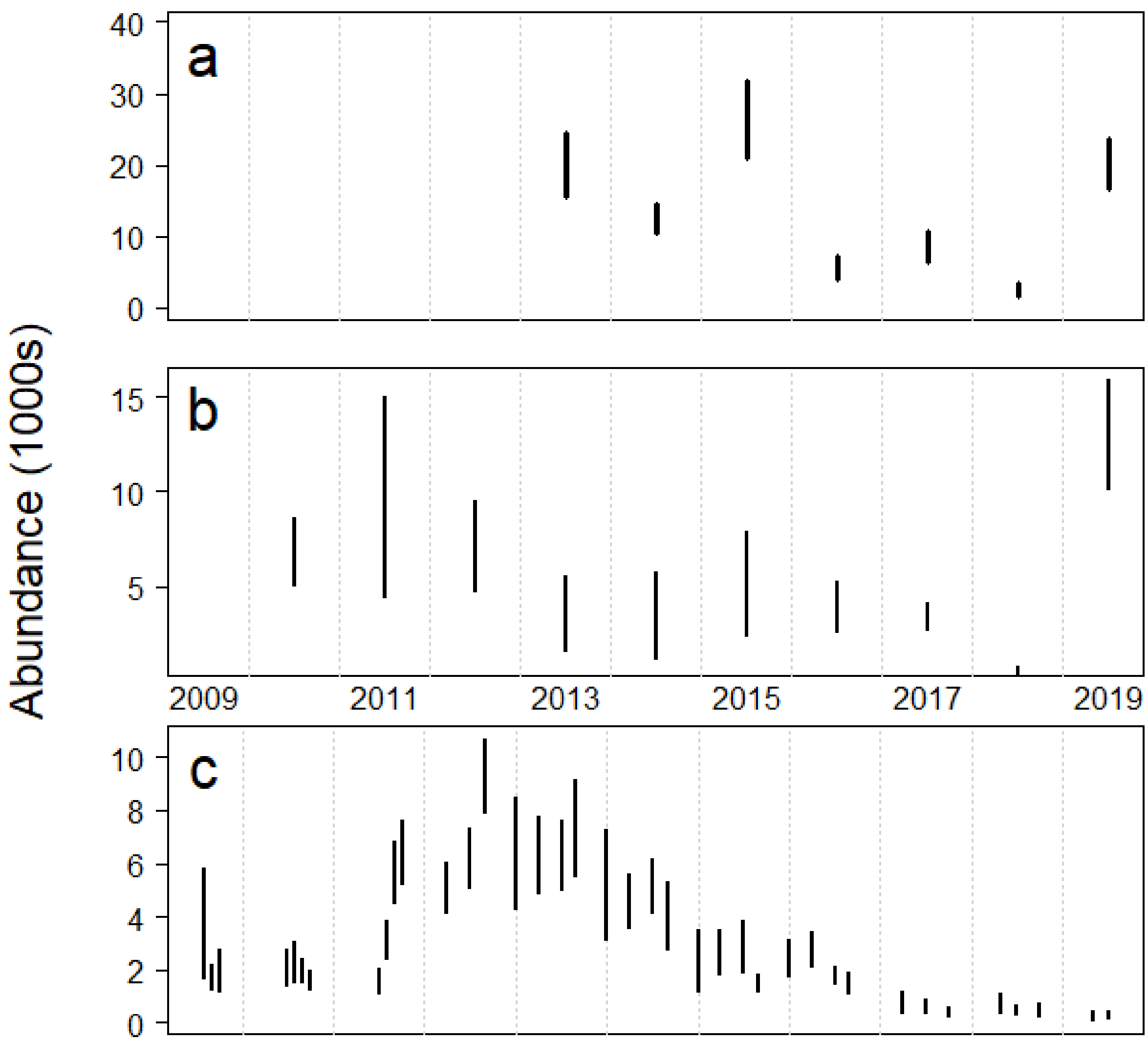

Figure 1. Plots of juvenile humpback chub abundance (<100mm total length -TL) from three sampling efforts: a) USGS June Little Colorado River (LCR) sampling trip from 2013-2019, b) USFWS fall monitoring of the LCR from 2010-2019 (courtesy of Randy Van Haverbeke, USFWS), and c) USGS monitoring of JCM reach in the Colorado River from 2009-2019. Panels a and b reflect only age-0 fish. The span of the error bars represent 95% credible intervals (a,c) or 95% confidence intervals (b). Abundance estimates from the JCM reach are obtained for near shore ecology trips from 2009-2011 (in July, August, September, and October) and from JCM trips in 2012-2019. JCM trips occurred either quarterly (from 2012-2016) or triannually (from 2017-2019) and were timed to occur in spring (April or May), summer (June or July), fall (September or October), and winter (January in 2012-2016 only).

For many decades, humpback chub that spawned in the LCR formed the vast majority of the overall CRe population. Since 2014, however, the catch of humpback chub in western Grand Canyon has been increasing (Van Haverbeke and others, 2017) and it is likely a larger portion of the overall CRe population is now found in western Grand Canyon. While our understanding of the drivers of the LCR population has matured in recent years following intensive demographic studies, we lack a similar understanding for the western Grand Canyon. Available data suggests that recent increases may be driven by only a few years of high juvenile production. During FY2021 and FY2022, we will continue studies of chub demography in the western Grand Canyon, which will allow us to determine baseline rates of growth and survival and allow us to estimate of abundance in this expanding population segment. Unfortunately, the cessation of mark-recapture efforts in FY2023, combined with the lack of seining data throughout this workplan means we will be unlikely to gain an understanding of the drivers of juvenile production and overall chub vital rates and will be unable to develop predictive models similar to the ones used in the LTEMP EIS for chub that spawn in the LCR.

To mostly satisfy BiOp Conservation Measures, 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 (G.2, G.3) in all years. We will monitor the western Grand Canyon population via continuation of mark-recapture in the Fall Canyon reach (JCM-west) during FY2021 and FY2022 (G.6), but will be forced to discontinue this sampling in FY2023, which will likely slow efforts to understand drivers in the western Grand Canyon, an objective listed in the BiOp Conservation Measures. We will also be discontinuing seining trips (not funded, G.8) in all years of the workplan, further hampering these efforts.

On the other hand, extensive sampling via the aggregation sampling (G.5) will continue in all 3 years, albeit with less effort in FY2022 than originally proposed. Mark-recapture data from these trips will be supplemented with data from autonomous passive integrated transponder (PIT) tag antennas, such as the LCR multiplexer cross-channel array (MUX) in the LCR and portable 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 (G.4). Lastly, since models developed under the previous workplan suggest that Chute Falls translocations help augment the LCR-spawning adult population, we propose continuation of Chute Falls translocations and monitoring by the US Fish and Wildlife Service (USFWS; G.7). We do not currently plan to analyze otoliths from incidental mortalities of age-0 fish collected over the last few years in the LCR to improve understanding of hatch dates, which would have helped us understand the degree to which LCR hydrology effect 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 (G.1).

3. Hypotheses and Science Questions

1) Adult fish condition (i.e., relative robustness) influences age-0 production in the LCR, such that poor condition results in decreased fecundity and(or) spawning rates.
2) Nonnative channel catfish consume a significant portion of age-0 production in the LCR and large channel catfish populations can limit age-0 production in the LCR.
3) The timing and magnitude of floods in the LCR determine hatch dates and survival of age-0 juveniles ultimately driving age-0 production in the LCR (not addressed in this workplan).
4) Changes in LCR geomorphology related to sand inputs and evacuation significantly alter habitat quality among years leading to variation in age-0 production in the LCR.
5) Humpback chub in western Grand Canyon display lower survival than humpback chub in the mainstem near the LCR leading to faster rates of population turnover (i.e., greater potential for rapid increases and declines in population size).
6) Humpback chub in western Grand Canyon display similar survival to humpback chub in the mainstem CR near the LCR adding to potential resilience of humpback chub in the CRe.
7) The number of humpback chub in western Grand Canyon is, at this point, comparable to the number of humpback chub that spawn in the LCR.

4. Background

Humpback Chub that Spawn in the LCR

Systematic monitoring of the LCR and JCM-east reach since 2009 has shown that juveniles are a sensitive life history stage because there is high variability in juvenile production from year to year and that outmigration (i.e., movement from LCR to the Colorado River) is sporadic and only occurs in certain years (Figure 1). This high variability in juvenile production stands in stark contrast to variability in adult abundance, which is more dampened with increases/decreases occurring over longer time intervals (i.e., more gradually; Figure 2). Determining the sources of variability in age-0 production would enable scientists to more accurately forecast future population dynamics under different management scenarios, improve assessment of management actions, and time management actions to be most effective.

This workplan will therefore focus on evaluating drivers of age-0 production to determine what factors lead to good (or bad) recruitment years. To achieve this goal, we will continue sampling of the LCR and JCM-east reach (which also informs estimates of adult abundance and helps meet BiOp Conservation Measures), as this information will help determine if recent declines in age-0 production are part of natural fluctuations or a declining trend that warrants a management response.

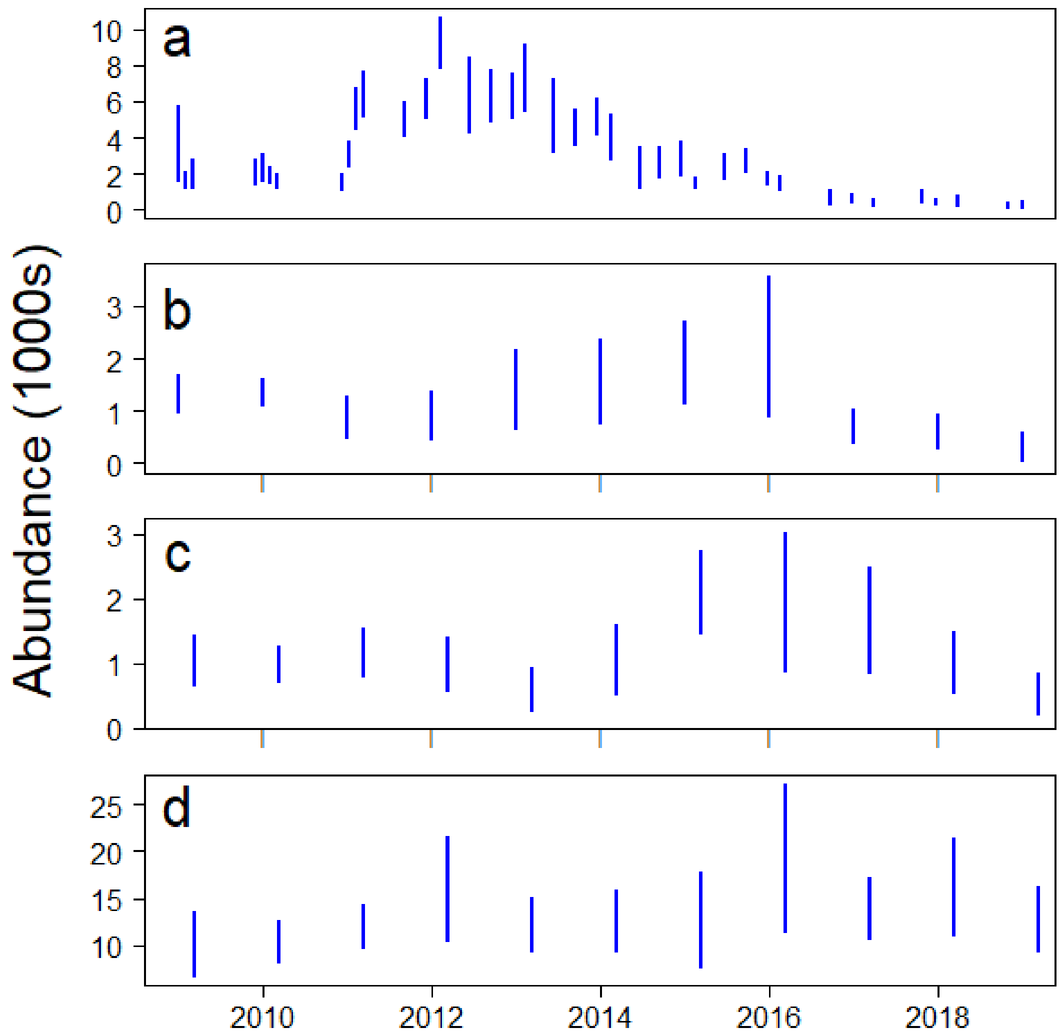

Figure 2. Abundance estimates for four size classes of humpback chub from 2009-2019. Estimates of juveniles (panel a; <100mm total length; TL), small subadults (panel b; 100-149mm TL) and large subadults (panel c; 150-199mm TL) are for the juvenile chub monitoring reach (JCM-east) whereas estimates of adult humpback chub (panel d; >200mm TL) pertain to all adults that spawn in the Little Colorado River. Note panel a is repeated from Figure 1. The span of the bars represent 95% credible intervals.

Assessment of juvenile humpback chub population dynamics relies on the following monitoring efforts: USGS-led sampling in the LCR (late June), triannual sampling in the JCM-east reach (spring, summer, and fall of each year), and USFWS-led spring and fall sampling in the LCR. These sampling efforts are designed to complement each other (Figure 3). The June LCR trip provides age-0 production estimates, as this sampling trip is timed to occur before midsummer monsoons, which is period of most juvenile outmigration to the Colorado River. Sampling in the JCM-east reach provides information to estimate juvenile abundance within the Colorado River – increases in abundance between successive trips reflect migration from the LCR as no spawning occurs in this reach of the Colorado River. Importantly, because growth is slow in the JCM reach (located in the mainstem CR), humpback chub remain as juveniles (<100mm TL) for multiple years and the abundance in a given year reflects both that year's production and carry-over from previous years. The fall USFWS trip provides an estimate of the number of age-0 fish that did not emigrate from the LCR.

Taken together, these abundance estimates illustrate the importance of the 2011 and 2012 cohorts, as these years not only resulted in increased production within the LCR, but also had high outmigration which increased juvenile abundance in the JCM reach. After 2012, there was a gradual decline in humpback chub (<100mm TL) as many of the fish that were from the 2011 or 2012 cohort slowly grew out of the <100mm TL size class and recruitment/outmigration has been low since 2013 (N.B. information from 2019 is incomplete as we do not have an estimate for fall 2019 in the JCM reach due to confounding in the final interval of open models). Although error bars are wide and overlapping, there is evidence to suggest that the 2011 and 2012 cohort led to future (lagged) increases in subadults and adults, and that the decline in juveniles from 2013-2018 has been followed by (lagged) decreases in small and large subadults in the JCM-east reach occurring in 2017 and 2018, respectively (Figure 2). Under these circumstances, we expect a future decline in adult humpback chub abundance, though the magnitude of this decline is uncertain.

One focus of this project during FY2021-23 will be improving our understanding of drivers of age-0 production. One well-established relationship is that without winter/spring floods in the LCR, age-0 abundance estimates are extremely low (see 2018 in Figure 1A; also Van Haverbeke and others, 2013). While the mechanism for this pattern is unknown, two prevalent hypotheses are that years without floods lack spawning cues for adult humpback chub and(or) that there is increased accumulation of fine sediments which are detrimental to survival of early life history stages. In years with at least some winter/spring flooding in the LCR, we propose a series of hypothesis to explain variation in age-0 production, including: (H.1) production is driven by adult fish condition, (H.2) production is driven by catfish predation, (H.3) production is driven by the timing and magnitude of winter/spring flooding, and (H.4) production is driven by changes in geomorphology, especially the accumulation and evacuation of sand in potential habitat for early life history stages.

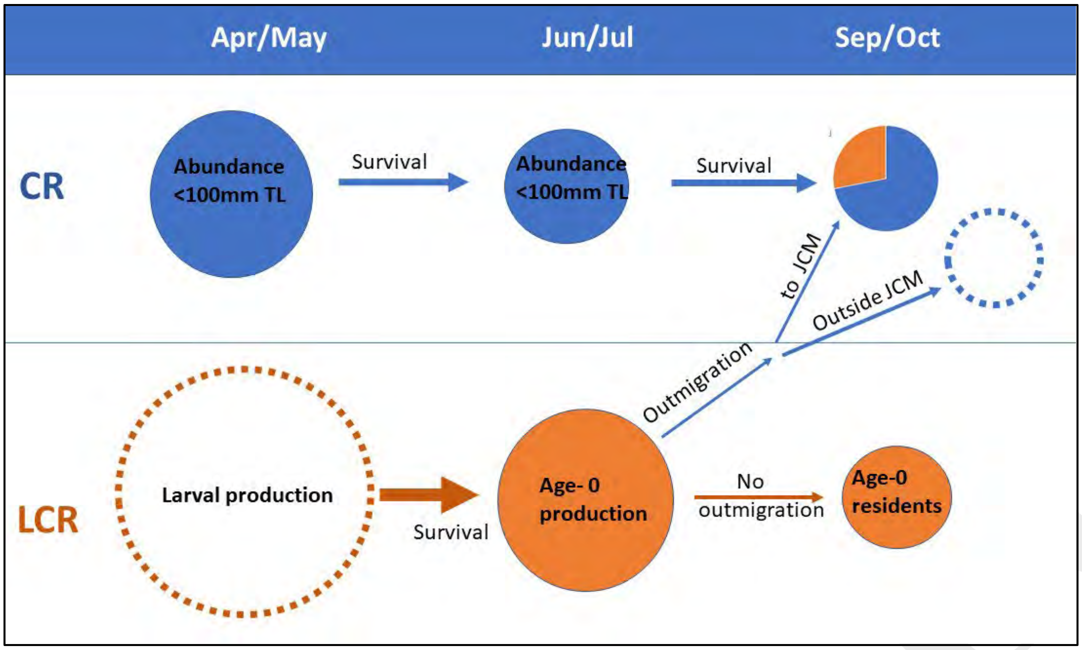

Figure 3. Conceptual figure depicting population dynamics of juvenile humpback chub from April to October. Filled circles represent abundances that are quantified through mark-recapture efforts and empty circles with dotted lines represent unsampled portions of the population that are not quantified. The upper half of the figure illustrates dynamics of juveniles in the Colorado River (CR), where growth is slow and individuals may remain <100mm total length (TL) for multiple years so that juvenile fish can be comprised of multiple age classes (e.g., age 0-3). Generally, additions to fish in the CR occur from outmigration from the Little Colorado River (LCR; typically during the monsoon season). The lower portion of the figure shows fish in the LCR where growth is fast, and dynamics pertain to age-0 individuals.

To test H.1, we will examine the relationship between food availability in the CR, the condition of adult humpback chub, and variation in age-0 production. To date, support for H.1 is equivocal. On one hand, most metrics of food availability and fish condition were high in 2011 and 2012, coincident with exceptionally high age-0 immigration into the JCM-east reach. On the other hand, food availability and fish condition in the mainstem Colorado River were low in the latter half of 2014 and age-0 production in 2015 was the highest seen since 2013. Testing this hypothesis relies on continued sampling associated with Projects E and F (in addition to Project Elements G.2 and G.3) and will help inform ecosystem models developed in E.3. While H.1 is a 'bottom-up' hypothesis explaining controls on age-0 humpback chub, H.2 suggests predation exerts a 'top-down' control on age-0 abundance.

Channel catfish have been shown to be predators of humpback chub in the LCR (Marsh and Douglas, 1997), but the population-level impacts of catfish predation on age-0 humpback chub abundance is unknown. Assessing H.2 would require more information about channel catfish abundance, and will be assessed in coordination with Project I. In contrast to H.1 and H.2, H.3 posits that age-0 production is primarily influenced by the timing and magnitude of spring/winter floods. We originally planned to conduct a preliminary study using existing staff to evaluate age (in days) and growth in otoliths of age-0 humpback chub from incidental mortalities collected from 2012-2020, however this element was not funded. Age/growth estimates from incidental mortalities could be used to assess variability in hatch dates across years and formulate more informed hypotheses about if (how) flooding conditions affect age-0 larvae. Lastly, to test H.4, we plan to begin annually monitoring channel characteristics using fixed transects during trips already scheduled to visit the LCR.

Humpback chub in Western Grand Canyon

Humpback chub catch in 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. Beyond this observation of variability in age-0 production, we lack a basic understanding of the drivers of survival, growth, juvenile production, and reach-wide adult abundance. Accordingly, we propose to continue to monitor humpback chub in western Grand Canyon in FY2021 and FY2022, and to focus analyses in the three following areas: 1) improve understanding of population turnover and vital rates (e.g., survival, growth, movement), and 2) obtain a reach-wide abundance estimate for the entire western Grand Canyon population. We also originally hoped to assess drivers of juvenile production in the western Grand Canyon, but without seining data and with JCM-west ceasing in FY2023, we doubt that we will have sufficient power to make meaningful interferences.

Better understanding of survival, growth, and movement will provide basic life history information about this new, burgeoning population; however, cuts may mean that we fall short of developing a predictive model for chub in the western Grand Canyon. Of particular interest is the "speed" of population dynamics as measured through rates of population turnover. "Fast" populations are capable of quicker increases (and decreases) and near-term predictions rely on an understanding of drivers (Winemiller, 2005; Quetglas and others, 2016). Predictions of slow populations are also aided by an understanding of drivers; however, near-term predictions can be based solely on an understanding of present size-structure. As an example, the population dynamics of resident chub in the LCR are relatively fast with size distributions changing substantially year to year, whereas the dynamics of chub in the JCM-east reach are much slower allowing some degree of prediction from size structure alone (Yackulic and others, 2014). Data collected during this workplan as part of JCM-west, suggest that humpback chub in western Grand Canyon have growth rates greater than in the JCM-east reach, but less than in the LCR.

Estimates of survival are less precise, so their relationship to the relatively high survival in JCM-east and relatively low survival rates in the LCR are still unclear. We propose two demographic hypotheses: survival in JCM-west will be closer to survival in the LCR and population dynamics will be relatively fast – creating the potential for relatively rapid increases and decreases (H.5). Alternatively, survival in JCM-west is closer to survival in the JCM-east reach creating a potential for relatively rapid increases in abundance, but slower declines and greater resilience to series of "bad" years (H.6).

Further collection of mark-recapture data through JCM-west and modeling of population dynamics may help differentiate between H.5 and H.6, although it is unclear if terminating JCM-west in FY2023 will allow for sufficient data to disentangle these hypotheses.

Additionally, we had hoped to assess age-0 dynamics to help determine potential drivers of production but are now doubtful that we will have sufficient data for these purposes. A better understanding of age-0 dynamics in western Grand Canyon might have helped biologists understand the sudden increase in humpback chub that occurred in 2014, and this could have implications for other imperiled humpback chub populations in the upper Colorado River Basin. Preliminary assessment of length-frequency histograms from humpback chub aggregations sampling suggests some patterns, but must be interpreted within caution as in most years lagged production (i.e., age-1 fish) are caught in greater numbers than age-0 fish and it is uncertain if these values are sufficiently accurate as they do not exactly agree with results from seining trips which may have more accurately reflected juvenile production. Potential drivers of age-0 production include food availability, water temperature, and the interaction between food availability and water temperature.

Our last objective is to obtain an abundance estimate for adult humpback chub in the western Grand Canyon population. Because success/failure of conservation measures are often based on abundance, an abundance estimate for the western Grand Canyon population would be useful for informing species-level conservation across the entire range of humpback chub (i.e., upper and lower Colorado River Basin). In addition, obtaining abundance estimates across a wide spatial range could allow biologists to evaluate spatial variability in humpback chub abundance and learn more about preferred habitat characteristics.

Although abundances provide useful information for managers, accurate, reliable abundance estimates are difficult to obtain because they require estimates of capture probability. Estimating capture probability requires more intensive studies, such as mark-recapture or depletion, which entail either more visits per year to the same site or more passes per visit. For this reason, mark-recapture studies are often not feasible over extensive spatial scales given time and financial constraints. In contrast to mark-recapture studies, studies that evaluate catch or catch per unit effort (CPUE) are less intensive and thus easier to conduct over larger spatial scales; however, the relationship between CPUE and abundance is more subject to bias and often has poorer precision (Harley and others, 2001; Korman and Yard, 2017).

One promising hybrid approach would be to obtain a better understanding of possible capture probabilities using mark-recapture methods, and then to apply this distribution of possible capture probabilities to catch data to obtain estimates of abundance. This method is most useful in situations where capture probability is influenced by measurable covariates (e.g., temperature, turbidity, water velocity).

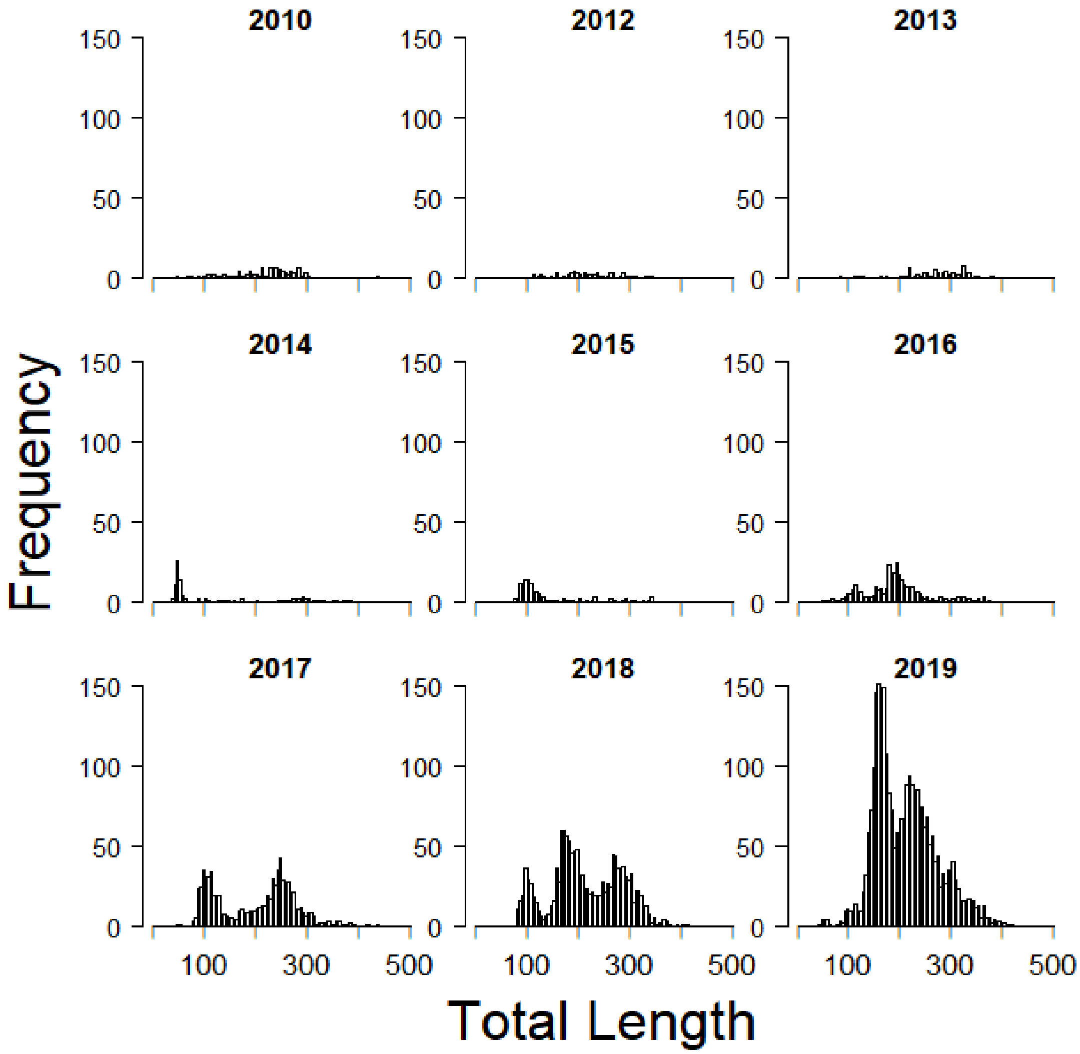

Figure 4. To attempt to standardize between trips, all humpback chub were captured using baited hoop nets. Importantly, across-year differences in frequency are not comparable as aggregations sampling included either one or two sampling trips in each year. However, within-year modes are informative as they highlight good recruitment years. Specifically, humpback chub 80-120 mm total length are typically age-1, thus large modes between 80-120 mm total length are likely indicative of successful age-0 production the previous year.

Accordingly, we propose to evaluate the effects of covariates on capture probabilities calculated from JCM-west sampling (G.6) and aggregation mark-recap events (G.5), and to combine information about capture probabilities with catch data from other aggregation sampling (G.5) to obtain an estimate of abundance for the western Grand Canyon adult humpback chub population. Abundance estimates of adult humpback chub in western Grand Canyon could be compared to abundance of LCR-spawning humpback chub to determine whether abundance in these two portions of the population are similar (H.7).

Translocated Humpback Chub

Translocations are an important management tool recognized by the LTEMP and BiOp as a key component of humpback chub management and a potential means to avoid mechanical removal of trout in the mainstem Colorado River near its confluence with the LCR. The 2016 Protocol Evaluation Panel (PEP) of the Glen Canyon Dam Adaptive Management Program (GCDAMP) fisheries program indicated there was a need to make the translocation program more rigorous quantitatively, to identify goals, and to design translocations to address key uncertainties about the effectiveness of this management action.

In response to the 2016 PEP's recommendation, the effectiveness of Chute Falls translocations was quantitatively assessed as part of the FY2018-20 workplan using a multistate mark-recapture model that allowed for movement between two segments in the LCR (~ river kilometer [rkm] 0-13.56 and 13.57-17.1) and the mainstem Colorado River.

Results show that translocated humpback chub upstream of lower Atomizer Falls (rkm 13.57-17.1) experience both faster growth (Stone and others, 2020) and higher survival compared to fish that remain in the lower segment, and both of these processes act to increase survival of juveniles to adulthood. Results also illustrated that downstream movement out of the upper LCR segment was substantial in some years, most notably the spring of 2010. Despite movement out of upper LCR in some years, comparison of two scenarios (A – translocate 300 juvenile humpback chub upstream of Chute Falls every year and B – do not translocate humpback chub) indicate that scenario A results in an extra ~410 adults (95% CI: 173-697) in the LCR spawning population compared to scenario B. This finding helps illustrate the effectiveness of translocations. Namely, translocations do augment the LCR spawning population and are a less expensive and less controversial management tool compared to trout removals. However, translocations may be limited in their potential for increasing adult numbers, as it is unclear to what extent the effort can be scaled up to produce larger changes to the adult humpback chub population.

5. Proposed Work

5.1. Project Elements

Project Element G.1. Humpback Chub Population Modeling

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

The objectives of this project are to provide better tools to understand the current state of the humpback chub resource (e.g., adult population size) and to predict its future state in response to management decisions. This project element is responsible for using data collected as part of monitoring efforts (G.2, G.3, G.4) to construct a multistate population model and provide life-stage specific abundance estimates of humpback chub in the LCR-spawning population each year. These abundance estimates are reported annually to stakeholders at the annual reporting meeting and are the basis for informing management decisions, such as whether or not nonnative trout removals should be conducted based on biological triggers.

In addition to the multistate model, the work conducted as part of the FY2018-20 workplan focused on: 1) evaluating skipped spawning dynamics in adult humpback chub in the LCR aggregation, 2) quantifying the impact of Chute Falls translocations on adult abundance in the LCR-spawning population, and 3) incorporating PIT-tag antenna detections into population models of humpback chub. Two manuscripts are in preparation assessing these three issues, and we hope to submit them in FY2020 or early in FY2021. In FY2021-23, we plan to: 1) continue to provide abundance estimates of various size classes in the LCR-spawning population to meet BiOp Conservation Measures, 2) assess drivers of age-0 production and outmigration in the LCR-spawning population, 3) evaluate population dynamics in JCM-west reach, 4) estimate 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, and 5) develop population models that incorporate size uncertainty for use in estimating abundance from antenna detections (where size is unobservable).

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

Kirk Young, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Randy Van Haverbeke, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office

Estimating the abundance of humpback chub adults in the LCR aggregation requires sampling in both the mainstem Colorado River and LCR. Sampling in the LCR during the spring along the lower 13.6 km of the LCR is the best opportunity to mark and recapture adults in the system as those adults that are present have much higher capture probabilities in the LCR than when they are in the mainstem. On the other hand, it is the adults captured during the fall that directly inform overall adult abundance estimates for the population as the overall precision in adult abundances is lowest in this time period (uncertainty in total adult abundances is determined primarily by uncertainty in mainstem abundances, not LCR abundances).

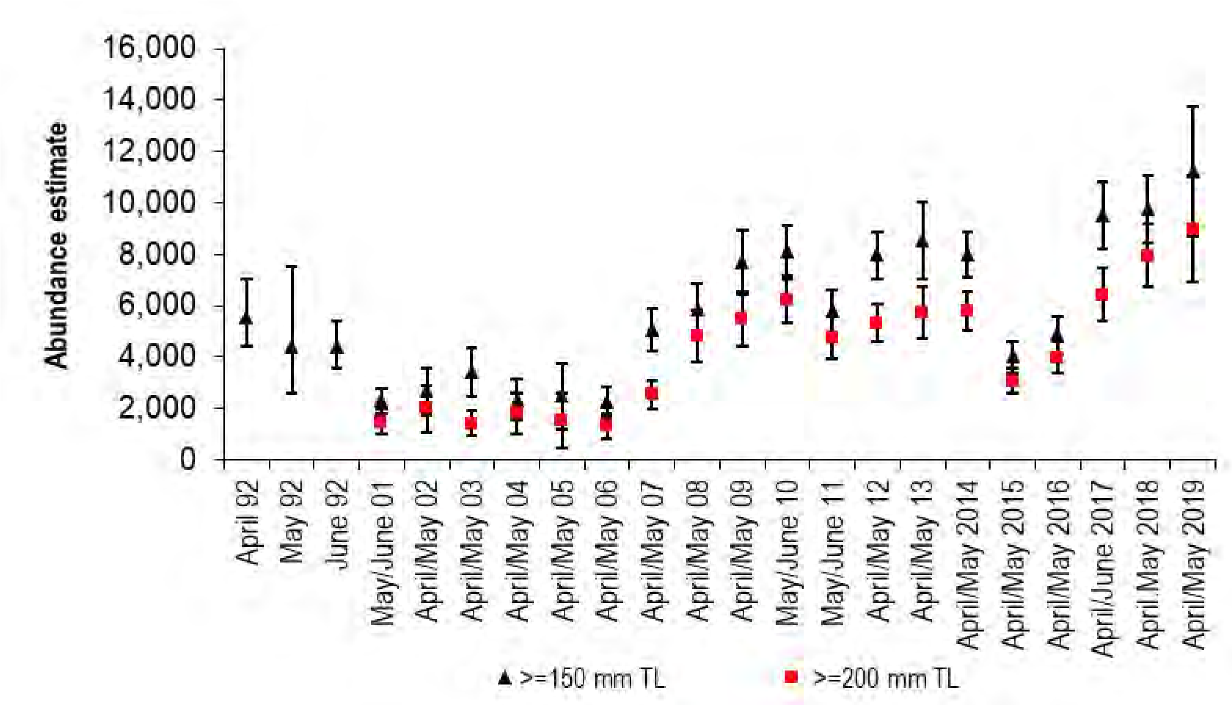

Figure 5. Spring abundance estimates of humpback chub in the Little Colorado River from USFWS monitoring.

Data collected during USFWS LCR monitoring trips are used to estimate spring and fall closed population abundance in the LCR for various size classes of humpback chub (e.g., 100-149 mm, 150-199 mm, > 150 mm, and > 200 mm TL; Figure 5), and during some years provides abundance estimates of other native fishes (Van Haverbeke and others, 2013).

In addition to adult spawning abundance, spring data also provide juvenile abundance estimates in support of humpback chub action triggers. Fall data provides abundance estimates for various size classes of humpback chub more representative of the overwintering or resident population. It also assists in determining outmigration of age-0 chub. Specific objectives for FY2021-23 (similar to objectives for previous years) are:

1) Determine length stratified estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm TL) in the lower 13.6 km of the LCR during the spring and fall – LTEMP BiOp and Action triggers.

2) Generate a population estimate of age-0 humpback chub (40-99 mm TL) during fall after some variable proportion of age-0 humpback chub have emigrated to the mainstem.

3) Collect data and implant PIT tags into fish in support of humpback chub population modeling. On average, ~2,200 PIT tags are implanted per year

on LCR spring and fall trips; 54% in the spring and 46% in the fall. During years with high production of age-0 humpback chub, fall proportions can jump to ~73% of tag output (e.g. 2019).

4) Collect additional data on fishes in the LCR such as size, species, sexual condition and characteristics, and external parasites (i.e., *Lernaea cyprinacea*).

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

Mike Yard, Fish Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC
Maria Dzul, Fish Biologist, USGS, GCMRC

This project element provides the data to estimate survival, growth and abundance of multiple size classes of humpback chub in the mainstem Colorado River just downstream of the LCR confluence. Data from this project element are used as follows:

1) To inform the multistate model, which generates abundance estimates for the humpback chub adult LCR aggregation and informs triggers associated with the BiOp,

3) To estimate rainbow trout and brown trout abundance near the LCR confluence to continue to track the relationship between rainbow trout and brown trout production in Lees Ferry and abundances near the LCR, and

4) To estimate age-0 humpback chub production and outmigration, which are highly variable from year to year and key to understanding whether pre-emptive rainbow trout management via Trout Management Flows or mechanical removal is needed to meet population targets (Yackulic and others, 2018),

5) To evaluate spawning dynamics and alternate life history strategies in adult humpback chub (Dzul and others, *in prep*), and

6) To monitor changes to humpback chub condition (a ratio of weight to length sometimes used to assess fish health/nutrition), which may provide valuable information for interpreting spawning dynamics.

We propose to retain the same amount of effort in FY2021-23 as in the FY2018-20 workplan, that is, three trips each year to the JCM-east reach (May, June/July and October) and one trip each year to the LCR (late June – before the onset of monsoon season).

JCM trips will use a variety of gear types to sample fishes (e.g., hoop nets, portable remote PIT-tag antennas, nighttime electrofishing), and LCR trips use hoop nets as well as seines and dip nets to target small, age-0 humpback chub.

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

Maria Dzul, Fish Biologist, USGS, GCMRC
Kirk Young, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Bill Kendall, USGS, Colorado State University
Dana Winkelman, USGS, Colorado State University
Charles B. Yackulic, Research Statistician, USGS, GCMRC

Unlike other monitoring types (e.g., hoop nets, electrofishing, seines) which require physical captures, PIT-tag arrays read and record codes from tagged fish that swim over antennas anchored to the river bottom or riverbank. Accordingly, these arrays provide a method for boosting recapture events without requiring additional fish handling. Importantly, these systems are particularly useful for detecting large (>250mm TL) humpback chub which are difficult to capture using hoop nets. In fact, adding antenna data from the LCR and Colorado River substantially changed inference from population models (Dzul and others, *in prep*). Specifically, models without antenna data underestimated the proportion and number of migratory adult humpback chub that moved into the LCR in spring months and also underestimated adult survival compared to models with these data (Figure 6). Taken together, these results illustrate that the benefit of including PIT-tag arrays is not solely based on their ability to increase detection probabilities for all humpback chub, but rather their ability to increase detection of a subset of the humpback chub population that is relatively invulnerable to capture. In FY2021-23, this project element will continue to provide data to track the timing of the humpback chub spawning movements, test hypotheses about trap avoidance, and inform population models.

PIT-tag array detections in the LCR includes continuous detections from two sources: a multiplexer system (MUX) and a network of shore-based single antennas (NET). The MUX and NET systems should complement each other well, as the MUX provides detection coverage across the entire channel width and the NET will provide additional detection data, which could help inform movement directionality. The MUX is comprised of two arrays located in the LCR, ~1.8 river km upstream of the confluence with the Colorado River. Installed in 2009 and 2011, these arrays are anchored to the riverbed and span the channel width. The MUX is outdated and no longer supported by the manufacturer (Biomark, Inc.).

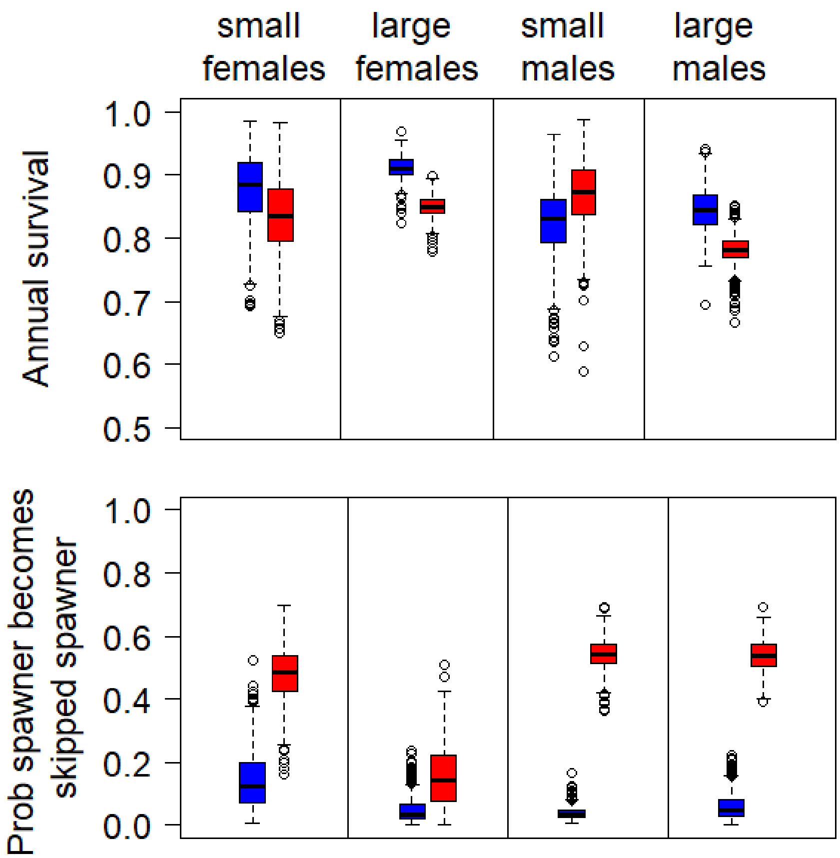

Figure 6. Comparison of migratory adult humpback chub annual survival (top panel) and spawning probability (bottom panel) for mark-recapture models with (blue) and without (red). Passive integrated transponder tag array detections. Estimates are specific to males and females, as well as for small (200-249mm total length; TL) and large (> 249mm TL) fish. Survival estimates pertain to humpback chub that move between the Colorado River and Little Colorado River to spawn. Spawning probabilities are inferred based on movement between the Colorado River and Little Colorado River and are represented by the probability a fish that spawns in year *t* does not spawn in the following year (*t*+1).

In 2019, the Bureau of Reclamation funded the construction and installation of a new MUX that is an improved design compared to the MUX array that is currently in the LCR. Installation of the new MUX was scheduled for May 30 - June 6, 2020 but will be postponed until fall 2020 due to concerns about COVID-19. Installation will entail removing the outdated MUX and anchoring the new MUX in the same location.

The NET design was installed in 2017 but evolved substantially as more was learned about how humpback chub swim up the LCR. Specifically, at first all NET antennas were initially clustered in the same location (rkm 1.3). This design was problematic in that detections from individual antennas were not independent, and this violated a common assumption of mark-recapture models. In 2019, the design was modified to include two clusters (each with four antennas), one placed near ~rkm 1.3 and the other ~rkm 2.1.

Because there is a large waterfall separating the two clusters, this design should be well suited for evaluating movement, as fish are unlikely to swim back and forth between clusters due to the (likely) large energetic expenditures required to upswim the waterfall. In FY2021-23 we propose continuing to fund maintenance of these two antenna systems in the LCR.

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

Kirk L. Young, Fish Biologist, USFWS
Randy Van Haverbeke, Fish Biologist, USFWS
Laura Tennant, Fish Biologist, USGS, GCMRC

Aggregations of humpback chub in Grand Canyon are biologically important because they potentially provide redundancy and resiliency for the species. Notably, this project element was key to first detecting the increase in humpback chub in western Grand Canyon in 2014 (Van Haverbeke and others, 2017) and, in turn, informing species-level conservation and spurring numerous research efforts to better understand drivers in this new population.

Annually monitoring the status and trends of humpback chub aggregations and conducting periodic surveys in between aggregations to identify additional aggregations are Conservation Measures listed in the BiOp.

This project will conduct one mainstem sampling trip per year focused on aggregations and one additional partial mainstem sampling trip in 2022 focused on areas between aggregations. The annual aggregations trip will focus on hoop net monitoring of the known aggregations (e.g., RM 30-36, LCR, Bright Angel, Shinumo, Stephens Aisle/Middle Granite Gorge, Havasu, Pumpkin Spring). The primary objective of this annual trip will be to continue a long-term CPUE index that has been constructed since the early 1990s (Persons and others, 2017).

In addition, these trips have been conducting closed mark-recapture estimates of various size classes of humpback chub (Figure 8) and flannelmouth sucker since 2017. Portable PIT-tag antennas will also be utilized to detect tagged fish, providing additional information on humpback chub, while reducing handling of fish. The secondary objective of this project element will be to help provide information about catch and capture probabilities, which will be used to obtain an abundance estimate for the western Grand Canyon humpback chub population.

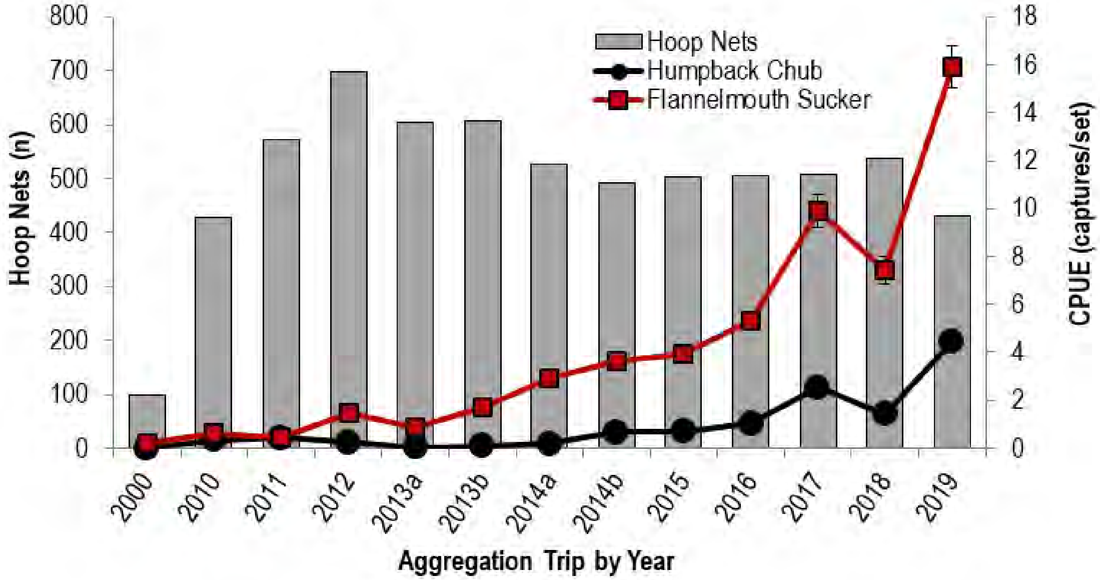

Figure 7. CPUEs of humpback chub and flannelmouth sucker (all size classes) paired with total hoop nets set for each Grand Canyon aggregation trip 2010-2019. Note in 2013 and 2014, two hoop netting aggregation trips (July, September) were conducted (from Van Haverbeke and others, 2020).

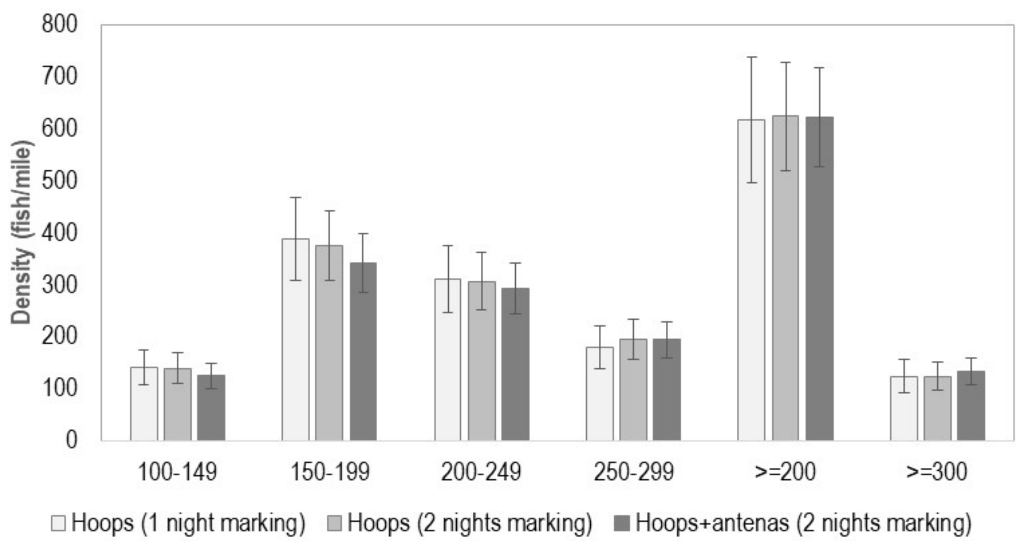

Figure 8. Densities (fish/mile) of humpback chub in size classes (mm) in Bridge City reach (river mile 236-238), Colorado River, September 2019. The comparative density estimates were calculated from closed mark-recapture abundance estimates using baited hoop nets in the marking event for one night, two nights, and with the addition of passive integrated transponder tag antennas as "marking" event gear (from Van Haverbeke and others, 2020).

Project Element G.6. Juvenile Chub Monitoring—West

Mike Yard, Fish Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC

In recent years, catch in humpback chub aggregations in western Grand Canyon have increased dramatically (Van Haverbeke and others, 2017), but little is known about the population dynamics of humpback chub in this reach. Understanding the drivers of this population was a goal identified in the Conservation Measures of the BiOp. Furthermore, the 2016 fisheries PEP specifically recommended additional study in the lower part of the CRe. To address these goals, regular monitoring of Fall Canyon (i.e., JCM-west) reach commenced in 2018. However, the decision to end this project element after FY2022 means we are unlikely to develop an understand of drivers but will likely develop a basic understanding of chub life history in this reach. Sampling the JCM-west reach in FY2021-22 will be similar to sampling in FY2018-20, occurring during the same trips (i.e., May, June/July, October) and using the same sampling methods as are currently employed as part of the JCM-east monitoring.

Because JCM-west monitoring visits the same site three times each year, this monitoring effort provides the framework for conducting mark-recapture studies that allow for estimation of abundance, survival, and growth across different life stages.

In turn, mark-recapture models from the JCM-west reach will allow biologists to assess population turnover rates and time lags in population dynamics (i.e., H.5-H.6), which will provide information about the resiliency of the population and context about if, or how, population dynamics relate to Glen Canyon Dam operations.

Comparing dynamics of the western Grand Canyon humpback chub population to that of the LCR-spawning population could also inform species conservation. In particular, if drivers are substantially different in these two groups, this may provide redundancy as dynamics will be asynchronous (Kerr and others, 2010). For example, different conditions in the unregulated LCR and highly regulated Colorado River could decouple age-0 production in the two rivers and lead to asynchronous dynamics. Asynchrony could also arise due to differences in phenology, which can be indirectly inferred based on seasonal comparisons of length-frequency distributions.

Specifically, whereas juveniles in the LCR-spawning population typically hatch in early- to mid-spring (i.e., likely late March to late April), juveniles in western Grand Canyon are more likely to hatch in late spring (May). Conversely, if drivers are similar in the LCR and western Grand Canyon, we might expect synchrony in the temporal population dynamics of the two groups. Synchrony would occur if the two groups are similarly affected by Colorado River water temperatures and (or) food availability. Unfortunately, we are unlikely to develop the understanding of drivers that would allow for assessment of redundancy, so these questions will likely take many more years to decades to answer using catch-based monitoring.

Project Element G.7. Chute Falls Translocations

Kirk Young, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Randy Van Haverbeke, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office

Translocation and monitoring of humpback chub upstream of Chute Falls has been in place as a conservation action in BiOps since 2002 (USFWS, 2002; 2011; 2016). We propose to continue translocating juvenile humpback chub to upstream of Chute Falls on an annual basis and to continue annually monitoring them. To date, 3,776 juvenile humpback chub have been translocated upstream of Chute Falls. In conjunction with translocation activities of humpback chub upstream of Chute Falls, we work collaboratively with the USFWS Southwest Native Aquatic Resources and Recovery Center at Dexter, NM to maintain a long-term genetic refuge of humpback chub and work collaboratively with NPS to provide juvenile humpback chub for translocation activities into Shinumo Creek and Havasu Creek.

5.2. Outcomes and Products

The work described here will lead to multiple peer-reviewed publications (e.g., research from similar projects in the FY2018-20 TWP led to 13 manuscripts that have been published or are in press and six annual reports). We will provide annual summaries of state variables and vital rates relevant to the BiOp (e.g., abundance, survival, recruitment, and growth rates) at the GCDAMP Annual Reporting Meeting each January. Also, we will provide more frequent summaries of some monitoring metrics to the GCDAMP and others if there is additional interest in further evaluating the response of humpback chub to any combination of LTEMP flow experiments.

6. References

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7. Budget

Fiscal Year 2021								
Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
G.1. Humpback chub population modeling	$103,619	$4,000	$7,000	$0	$0	$0	$16,047	**$130,666**
G.2. Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$12,640	$0	$14,200	$96,789	$342,506	$0	$27,583	**$493,718**
G.3. Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$113,365	$0	$13,000	$224,982	$0	$0	$49,189	**$400,536**
G.4. Remote PIT tag array monitoring in the LCR	$22,482	$0	$6,000	$7,032	$0	$0	$4,972	**$40,487**
G.5. Monitoring HBC aggregation relative abundance & distribution	$10,060	$0	$14,100	$55,220	$96,240	$0	$14,000	**$189,621**
G.6. Juvenile chub monitoring - Western Canyon	$68,450	$0	$17,600	$186,387	$0	$0	$38,141	**$310,578**
G.7. Chute Falls translocations	$4,962	$0	$2,600	$15,230	$67,520	$0	$5,216	**$95,528**
Total Project G	**$335,579**	**$4,000**	**$74,500**	**$585,640**	**$506,266**	**$0**	**$155,149**	**$1,661,134**

Fiscal Year 2022								
Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
G.1. Humpback chub population modeling	$112,117	$4,000	$2,000	$0	$0	$0	$25,986	**$144,102**
G.2. Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$20,245	$0	$14,200	$105,120	$342,506	$0	$40,980	**$523,051**
G.3. Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$112,285	$0	$13,000	$231,043	$0	$0	$78,392	**$434,720**
G.4. Remote PIT tag array monitoring in the LCR	$32,193	$0	$6,000	$8,375	$0	$0	$10,245	**$56,812**
G.5. Monitoring HBC aggregation relative abundance & distribution	$8,763	$0	$24,100	$84,774	$110,740	$0	$29,202	**$257,579**
G.6. Juvenile chub monitoring - Western Canyon	$52,788	$0	$17,600	$191,056	$0	$0	$57,518	**$318,962**
G.7. Chute Falls translocations	$5,061	$0	$2,600	$16,915	$67,520	$0	$7,432	**$99,529**
Total Project G	**$343,451**	**$4,000**	**$79,500**	**$637,284**	**$520,766**	**$0**	**$249,755**	**$1,834,756**

Fiscal Year 2023								
Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
G.1. Humpback chub population modeling	$113,931	$4,000	$2,000	$0	$0	$0	$33,581	**$153,512**
G.2. Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$15,488	$0	$14,200	$105,540	$342,506	$0	$48,139	**$525,873**
G.3. Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$133,696	$0	$13,000	$267,151	$0	$0	$115,877	**$529,724**
G.4. Remote PIT tag array monitoring in the LCR	$46,303	$0	$6,000	$7,725	$0	$0	$16,808	**$76,835**
G.5. Monitoring HBC aggregation relative abundance & distribution	$14,100	$0	$14,100	$59,153	$96,240	$0	$27,346	**$210,940**
G.6. Juvenile chub monitoring - Western Canyon	$0	$0	$0	$0	$0	$0	$0	**$0**
G.7. Chute Falls translocations	$5,163	$0	$2,600	$16,615	$67,520	$0	$8,851	**$100,749**
Total Project G	**$328,681**	**$4,000**	**$51,900**	**$456,184**	**$506,266**	**$0**	**$250,602**	**$1,597,633**

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

Project Element G.6. Juvenile Chub Monitoring—Western Canyon

Mike Yard, Fish Biologist, USGS, GCMRC
Charles B. Yackulic, Research Statistician, USGS, GCMRC

The decision to end this project after FY2022 will likely mean that we are unable to develop an understanding of drivers in the Western Grand Canyon in the near future and thus unable to develop recommendations and robust predictive models to aid management. We may also not be meeting a conservation measure.

Project Element G.8. Backwater Seining

Charles B. Yackulic, Research Statistician, USGS, GCMRC
Mike Yard, Fish Biologist, USGS, GCMRC
Laura Tennant, Fish Biologist, USGS, GCMRC

Temporal variability in age-0 production is often high, but drivers affecting age-0 dynamics are poorly understood. Juvenile native fish, including humpback chub, often occur in backwaters at higher densities than in nearby near-shore habitat (Dodrill and others, 2015). While no study has ever established a link between backwater availability and humpback chub demographics (despite numerous attempts), they do represent habitat in which capture probabilities are much higher – leading to relative abundance indices that are much more statistically stable than those based on random sampling (another form of relative index with less precision).

For this reason, a better understanding of how backwater catch rates serve an index of population size would improve long-term assessment of native and nonnative fish populations (Dodrill and others, 2015). Because backwater seining targets age-0 fishes, it helps complement humpback chub aggregations sampling (G.5), which tends to focus efforts on capturing subadult and adult fish. Data from backwater seining trips would help differentiate good and bad years of age-0 production throughout the Colorado River, which in turn would help inform if (how) Glen Canyon Dam operations affect native fish production (Van Haverbeke and others, 2017). This project would have conducted one mainstem sampling trip per year in September.

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

Kimberly Dibble, Fish Biologist, USGS, GCMRC
Kirk Young, Fish Biologist, USFWS, Arizona Fish and Wildlife Conservation Office
Charles B. Yackulic, Research Statistician, USGS, GCMRC
Maria Dzul, Fish Biologist, USGS, GCMRC

Life history and spawning ecology of desert fishes are hypothesized to be dependent on spring flood conditions (Tyus and Karp, 1990; Brouder, 2001). The hydrothermal regime of the lower 13.56 km of the LCR is relatively unmodified, and large floods often occur in the winter and spring, at a time that precedes or overlaps with humpback chub spawning. Furthermore, there is substantial yearly variability in the magnitude and timing of winter/spring floods, so that in some years no flooding occurs (e.g., winter of 2017-2018), whereas other years show variability in the magnitude, duration, and timing of elevated flows (Figure 9). Like flow, abundances of age-0 humpback chub in the LCR are highly variable from year to year (Figure 1A), but correlating age-0 abundances with flow patterns does not suggest any obvious link between floods and age-0 production (except that the observation that years without floods have poor recruitment—see Van Haverbeke and others, 2013). Accordingly, more fine-scale temporal information about humpback chub larval life history is needed to assess if (how) spawning and larval dynamics are linked to hydrologic conditions. For example, there might be a critical period in the development of larvae when floods are necessary (e.g., dispersal) or detrimental (e.g., siltation) for survival. In addition to interannual differences in age-0 abundances, there is also substantial interannual variability in the size distributions of age-0 humpback chub, implying either variability in hatch dates or growth across years.

Disentangling these hypotheses with conventional mark-recapture methods would require a large effort that would be beset by difficulties in capturing, identifying, and handling larval fishes. An alternative tool for assessing hypotheses would be to obtain estimates of hatch date and larval growth from daily rings imprinted on fish otoliths, a calcified structure located in the inner ear (Campana and Jones, 1992; Bestgen and Bundy, 1998). Hatch date distributions and growth estimates obtained from otoliths could be used to explore hypotheses about how interannual differences in the timing and magnitude of floods affect age-0 production (Korman and

Campana, 2009). Furthermore, assessment of otoliths could provide preliminary estimates of individual variability in growth and develop relationships between size and hatch dates. Lastly, comparison of otoliths from the lower (rkm 0-4.5) and upper (rkm 4.5-13.56) LCR could help assess why age-0 fish captured in the lower LCR are typically smaller than their counterparts in the upper LCR (i.e., are chub in the lower LCR born later or do they grow slower?). Instead of sacrificing fish intentionally for this project, we had proposed to use otoliths from existing (incidental) mortalities from 2012-2021. Currently there are approximately 150 mortalities of age-0 fish that could be used for the analysis, and any mortalities collected in 2020 and (potentially) 2021 could also be used.

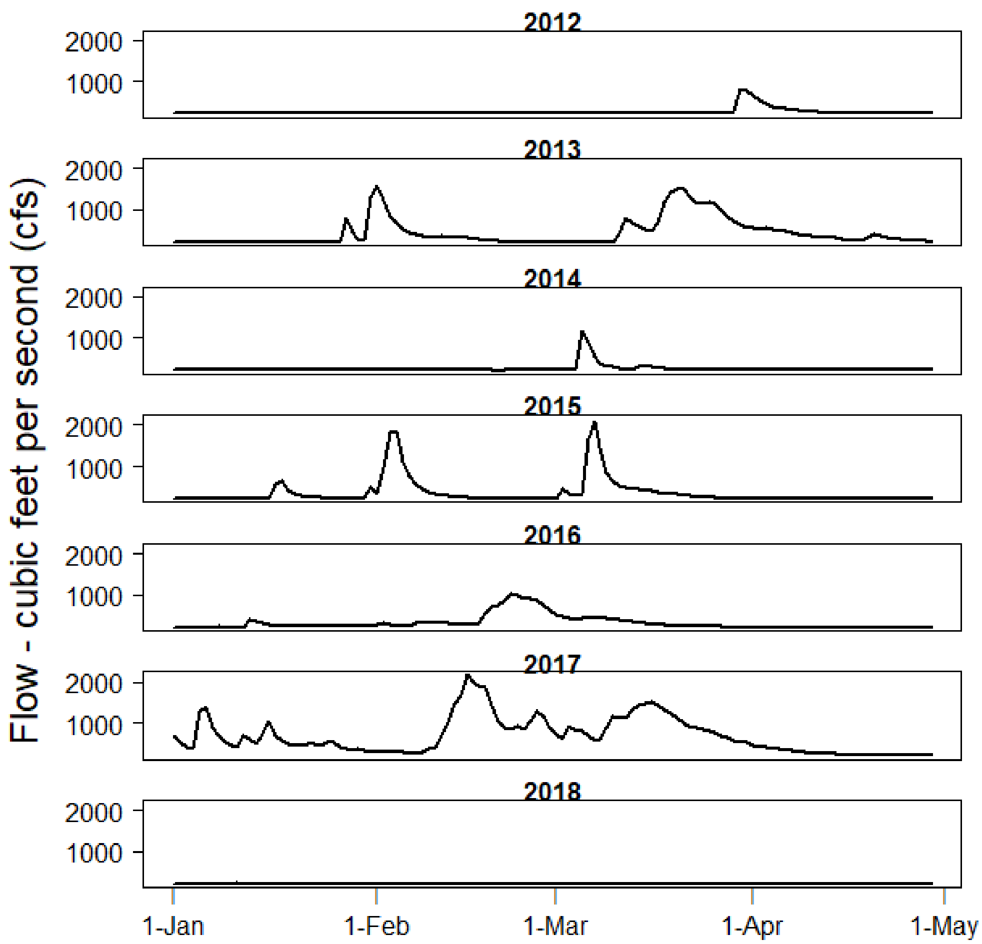

Figure 9. Flow of the Little Colorado River measured at gage 09402300 (LCR near Desert View ~rkm 1.0) from 1-Jan to 1-May from 2012-2018.

Project H: Salmonid Research and Monitoring

1. Investigators

Kimberly Dibble, Fish Biologist, U.S. Geological Survey, GCMRC
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2. Project Summary and Purpose

The Long-Term Experimental and Management Plan (LTEMP) (U.S. Department of Interior, 2016) provides the necessary long-term framework for assessing specific operations at Glen Canyon Dam (GCD), as well as other types of management actions conceived during and implemented over the next 20-year period. For this reason, the Salmonid Research and Monitoring Project was developed having the long view, with a means to revise and respond to unanticipated and emerging risks (e.g., brown trout). The study design described in the previous workplan still remains relevant for 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 trout population dynamics. Clearly, population responses are sometimes confounded by extrinsic factors (e.g., nutrients, see Project E) that act independent of flows or because of multiple management actions that have been applied concurrently within a given year (e.g., 2018 Summer Macroinvertebrate Production Flows, ‘Bug Flows’, and Fall High Flow Experiments, ‘HFEs’).

These circumstances make it difficult for resolving cause and effect relationships in a timely fashion. Although monitoring programs (e.g., Project Element H.1) are important for documenting long-term population trends and characteristics such as catch-per-unit-effort, size distribution, and occurrence and trends, monitoring as a sole method of data collection is not an effective approach in time or cost for determining causation, particularly when quantifying and separating out effects from complex interactions that occur among multiple factors (e.g., flow, fish density, nutrients). In order to study multiple flow treatments and avoid potential confounding factors, we propose to continue using a seasonal sampling design described in the FY2018-20 Triennial Work Plan (TWP) with spatial replication to assess trout responses to experimental flows and other factors within and across years.

However, due to budget constraints in the FY2021-23 TWP we will downscale the scope of this sampling design. FY2021 sampling will continue as the previous sampling design (four trips, three sub-reaches), but starting in FY2022 we will only sample one sub-reach per trip, representing a significant reduction in field sampling effort.

As a goal, protection of the endangered humpback chub near the Little Colorado River (LCR) is one of the highest priorities of the Glen Canyon Dam Adaptive Management Program (GCDAMP), but a concurrent priority is to maintain a high-quality rainbow trout sport fishery upstream from Lees Ferry in Glen Canyon. As such, rainbow trout were an important component in the development of LTEMP for GCD operations, and thus were a major consideration in the flow decisions in the selected alternative in the LTEMP Record of Decision (ROD; U.S. Department of Interior, 2016b). Yet, high trout abundance is not the only factor that limits humpback chub abundance at the LCR (e.g., temperature, prey, and turbidity) (Yackulic, 2018), as a population has survived multiple periods of high trout abundance (1998-2001, 2008-2009, 2011-2014, 2017-2019) (Coggins and others, 2011; Korman and Yard, 2020).

As such, Trout Management Flows (TMFs) proposed in the LTEMP were designed to limit rainbow trout recruitment and dispersal out of Lees Ferry (Korman and others, 2011a; Korman and others, 2011b; Korman and others, 2016; Yard and others, 2016) 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 from Lees Ferry over the past few years (2015-2019). Given this new development, it is unclear whether the expansion of brown trout will disrupt the balance between salmonids and endangered native fishes downstream, the rainbow trout fishery in Glen Canyon, and the degree to which flow manipulations can be used to manage rainbow and brown trout.

A major component of the proposed study elements, described herein, focus on how experimental flows will influence recruitment, growth, survival, and dispersal of rainbow trout in Glen and Marble Canyons. However, management of the rainbow trout fishery cannot occur in a vacuum given the recent increase of brown trout in Glen Canyon. Small numbers of brown trout have been present in the canyon since the dam was built (Minckley, 1991), but have increased following a time period associated with frequent fall HFEs (Runge and others, 2018). It is currently unclear whether this flow relationship is causal or coincidental, but research is needed to further examine if the proposed flow manipulations help or hinder the expansion of brown trout.

Other aspects of the flow regime and non-flow factors can also explain recent increases in brown trout. These include increases in macrophyte abundance due to reductions in diel variation in flow starting in the early 1990s (McKinney and others, 1999), and warmer water temperatures due to low reservoir elevations from the persistent 21st century drought may provide a physiological advantage for brown trout as an apex predator (Korman and others, *in review*).

However, good comparative studies of temperature tolerances made between rainbow trout and brown trout are uncommon, and at best thermal differences are nuanced (e.g., prey availability and prey size).

Brown trout are superior competitors in other tailwater systems and typically are not stocked past their initial introduction (Dibble, unpublished data), and are known to be voracious predators of small-bodied native fishes (Yard, 2011). It is therefore prudent and necessary to not only evaluate the effect of experimental flows on rainbow trout, but also to examine how brown trout populations may respond to such flow manipulations. Furthermore, competitive interactions between brown trout and rainbow trout may impact each other's survival and recruitment rates. Good growth and condition of rainbow trout occurred in late 2016 and 2017, which contributed to high rainbow trout recruitment in 2017, and its likely downstream movement.

The only year since 2015 without a substantive catch of age-1 brown trout also occurred in 2017, which was also the year with elevated recruitment of rainbow trout. Therefore, it is possible that a larger or healthier population of rainbow trout could help keep the brown trout population in Glen Canyon in check. It could be that higher levels of rainbow trout spawning in winter and spring of 2017 reduced recruitment of brown trout by redd (i.e. spawning bed) superimposition or other competitive effects (Scott and Irvine, 2000; Nomoto and others, 2010). Thus, policies aimed at reducing rainbow trout recruitment in Glen Canyon have the potential to backfire if they inadvertently lead to an increase in brown trout abundance. A better understanding of the interaction between rainbow and brown trout in Glen Canyon is therefore critical, and a major aim of the revisions made in the proposed workplan, herein.

This proposal uses a combination of field, modeling, and laboratory techniques to evaluate the response of rainbow trout and brown trout to experimental flows including TMFs, HFEs, equalization flows, and Bug Flows, as well as other management actions like the proposed incentivized take harvest (Runge and others, 2018). First, Project Element H.1 extends the long-term monitoring of rainbow trout in Lees Ferry by Arizona Game and Fish Department (AGFD), which provides a baseline for assessing the status and trends of rainbow trout, and more recently brown trout. Second, this element continues with its citizen science concept to gather data on angler catch quality in combination with ongoing creel surveys. The other three remaining study elements described below (H.2, H.3, H.4) are research and not monitoring, thus are focused specifically on determining how the effects of experimental flows will influence recruitment, growth, survival, and dispersal and by extension the abundance of rainbow trout and brown trout in Glen Canyon and in downstream reaches.

Project Element H.2 capitalizes on the knowledge gained from the FY2018-20 TWP, as well as the Natal Origin (NO) Project (2011-2017). As mentioned above, it uses the same Trout Reproductive and Growth Dynamics (TRGD) sampling design (described in Project H.1 of the FY2018-20 TWP) that focuses on juvenile and adult trout (rainbow trout and brown trout, ≥ 75 mm fork length) captured during quarterly mark-recapture trips. However, due to budgetary constraints in the FY2021-23 TWP, field sampling and the mark-recapture effort associated with the TRGD project will be reduced from three sub-reaches to one sub-reach. This will decrease the proportion of habitat sampled in Glen Canyon and will likely affect inferences made from the data for both rainbow and brown trout. The analytical components of H.2 are sizeable, which include a combination of abundance and vital rate estimates for recruitment, growth, and survival. These estimates are to be made for 1) rainbow trout population dynamics in Glen Canyon, 2) brown trout population dynamics in Glen Canyon (results will also be used to determine the efficacy of the incentivized harvest of brown trout in Glen Canyon [Project Elements H.4 and J.2]), 3) trout sexual maturation in Glen Canyon, 4) rainbow trout and brown trout young of year (YOY) catch indices in Marble Canyon at House Rock (52 river km downstream from Glen Canyon Dam; Project Element G.3), and 5) rainbow trout and brown trout population dynamics in the Juvenile Chub Monitoring reach near the LCR confluence (JCM-east; Project Element G.3).

Project Element H.3 is specifically focused on early life history stages of brown trout that are often too small developmentally to capture using conventional sampling methods (Project Element H.2). Therefore, a Brown Trout Early Life Stage Survey (BTELSS) will be conducted monthly (January-May) with objectives to 1) understand early life stage vital rates for YOY brown trout in Glen Canyon, 2) assess hatch and swim-up dates to identify when brown trout are likely to be emerging from gravel redds, and 3) identify habitat preferences for low angle (cobble bars, vegetated sand bars, debris fans) and high angle (talus) nearshore habitat to understand whether brown trout could be vulnerable to flow manipulation.

Finally, Project Element H.4 uses data collected from Project Elements H.1 and H.2 to develop a rainbow trout recruitment and outmigration model that predicts the response of rainbow trout to alternative flows and physical conditions in the CRe. This outmigration model can be used to evaluate the ability of alternative monitoring designs to detect rainbow trout responses to LTEMP flow alternatives. Secondly, it provides an alternative method for forecasting high recruitment years to better inform managers in the TMF planning stages. Additional work proposed in H.4 will focus on brown trout population modeling, estimating the efficacy of the National Park Service (NPS) brown trout incentivized harvest program, and understanding the population dynamics of rainbow trout in Lees Ferry. Collectively, these four project elements aim to resolve critical uncertainties about the response of rainbow trout and brown trout to experimental flows proposed in the LTEMP that are now the basis for its associated ROD (U.S. Department of Interior, 2016b).

3. Hypotheses and Science Questions

Most of the science questions, as originally proposed in the FY2018-20 TWP, remain relevant now; however, we have revised the list, placing more emphasis on brown trout, because of the increasing risk posed by this species in Glen Canyon.

1) What are the effects of TMFs on trout (rainbow and brown) survival, recruitment, growth, and dispersal?
2) What are the effects of spring and fall HFEs on trout recruitment, dispersal, and growth?
3) What controls trout dispersal from Glen Canyon into Marble Canyon, and the quantity reaching the LCR?
4) What factors control the quality of the rainbow trout fishery?
5) Why are young brown trout (< 75 FL [fork length]) less susceptible to capture by electrofishing earlier in the year?
6) What factors regulate brown trout population dynamics in Glen Canyon, and if control measures are implemented, what is the efficacy of those management actions?

4. Background

The LTEMP and ROD identified potential flow experiments including TMFs and low summer flows to improve conditions for fish, Bug Flows to benefit the food base, and spring and fall HFEs to improve sediment conditions and rebuild sandbars (U.S. Department of Interior, 2016a, b). TMFs were originally proposed to limit rainbow trout recruitment in Glen Canyon with the intent of reducing boom-and-bust cycles in the Lees Ferry fishery and limiting dispersal of rainbow trout from Glen Canyon to the LCR, thereby benefitting the humpback chub population downstream. The conceptual model used in the final LTEMP Environmental Impact Statement (EIS), however, did not adequately account for some of the flow characteristics necessary for designing an effective stranding flow in Glen Canyon.

Secondly, due to the further increase in brown trout populations, interest has been expressed in using TMFs to limit their recruitment as well. Flow characteristics for stranding brown trout will likely be similar to rainbow trout except for the timing of emergence (February-April), which is prior to rainbow trout (May-July). Field verification is warranted for both the timing of brown trout emergence and the similarity of their habitat requirements relative to rainbow trout. Currently, the Grand Canyon Monitoring and Research Center (GCMRC) is conducting an extensive literature review on fish stranding, which will be completed by the end of 2020.

Findings from this review will be provided to managers to help inform decisions about flow design elements and the uncertainties in optimizing the effectiveness of TMFs at reducing large recruitment events while minimizing negative side-effects.

Although fall HFEs have been the most common experimental flow evaluated to date, their effect on trout growth remains weak and inconclusive at this time (Yard and Korman, 2020). Concerns were raised earlier by the angling community that fall HFEs reduce the aquatic food base during the fall season, a period when rainbow trout growth is already low, having negative effects on the population and fishery. Preliminary analysis, however, suggests that the rainbow trout population crash (2013-2014) was more likely related to the reduction in nutrients (i.e., Soluble Reactive Phosphorus; SRP) which precipitated a decrease in macroinvertebrate production rates, rather than due to a disturbance effect from experimental flows (Yackulic, 2020; Korman and others, *in review*). Therefore, it is likely that other extrinsic factors are influencing trout growth rates and that more replication across years with and without HFEs is needed to determine if there is a measurable effect related to this type of flow. Also, Bug Flows were identified as an alternate flow regime in the ROD that could be used to enhance the aquatic food base which, in turn, could increase growth rates of rainbow trout in Glen Canyon and native fishes downstream. To date, two summer Bug Flows have been completed (2018-2019), and a third year is currently underway. While Bug Flows have the potential to influence rainbow trout recruitment and growth, it is unclear how such flows will influence brown trout populations.

Brown trout are highly piscivorous (Yard and others, 2011) and compete with nonnative and native fish species (Hearn, 2011; Kaspersson and others, 2013). Their recent expansion in Glen Canyon poses a significant threat to the rainbow trout fishery and likely to endangered humpback chub populations residing downstream in and near the LCR. In the past, management actions have included labor-intensive mechanical removal of rainbow trout and brown trout at the LCR confluence and in Bright Angel Creek (Makinster and others, 2010). However, the high abundance of YOY brown trout in Glen Canyon may require management actions to reduce recruitment before recruits become reproductively mature adults that may move downstream.

In 2008, large numbers of YOY rainbow trout were produced in Glen Canyon following a spring HFE (Korman, 2011a), some of which may have subsequently dispersed downstream (Korman, 2012). In the ROD, a two-year moratorium was imposed due to the possible relationship between spring HFEs and trout recruitment. The moratorium ended in 2019, so sediment-triggered spring HFEs are now allowed. In addition, recent recommendations by DOI (Petty, 2019) direct managers to consider conducting other higher spring releases within GCD power plant capacity. These circumstances may provide researchers with opportunities to further evaluate early life stage responses of trout to alternative flows; particularly, flow effects on stranding of the early life stages of brown trout.

Changes in flow velocity, magnitude, duration, and timing of GCD operations proposed in the LTEMP to manage rainbow trout populations may also be used as tools to manage brown trout recruitment and survival since such flows may fall within a timeframe when the two trout species are in their most vulnerable life history stages. Recent synthesis of brown trout data from regulated rivers across the western US found that brown trout recruitment is inversely related to flow velocity (Dibble and others, 2015), which may be due to energetic constraints imposed by high flows. Data from other tailwaters indicate that natural flooding events, like HFEs released from GCD, can have a significant negative effect on brown trout populations.

Winter-timed floods can decrease recruitment by scouring eggs and alevins from gravel redds (Strange and Foin, 1999; Wenger and others, 2011), while spring floods can decrease survival following emergence via energetic constraints (Cattanéo and others, 2002; Budy and others, 2008; Jonsson and Jonsson, 2009). While fall HFEs have occurred concurrently with the increase in brown trout recruitment, there is no causal link between the two phenomena. Brown trout routinely spawn in late fall to early winter (November-January), as follows, fall HFEs typically implemented in November may function to expurgate fine sediment accrued in spawning bars just prior to spawning. Yet, recent catch data for Glen Canyon (Yard and Korman, 2020) would suggest that years with and without fall HFEs have had no measurable effect on the annual spawning success of brown trout recruitment in the following year (Figure 1).

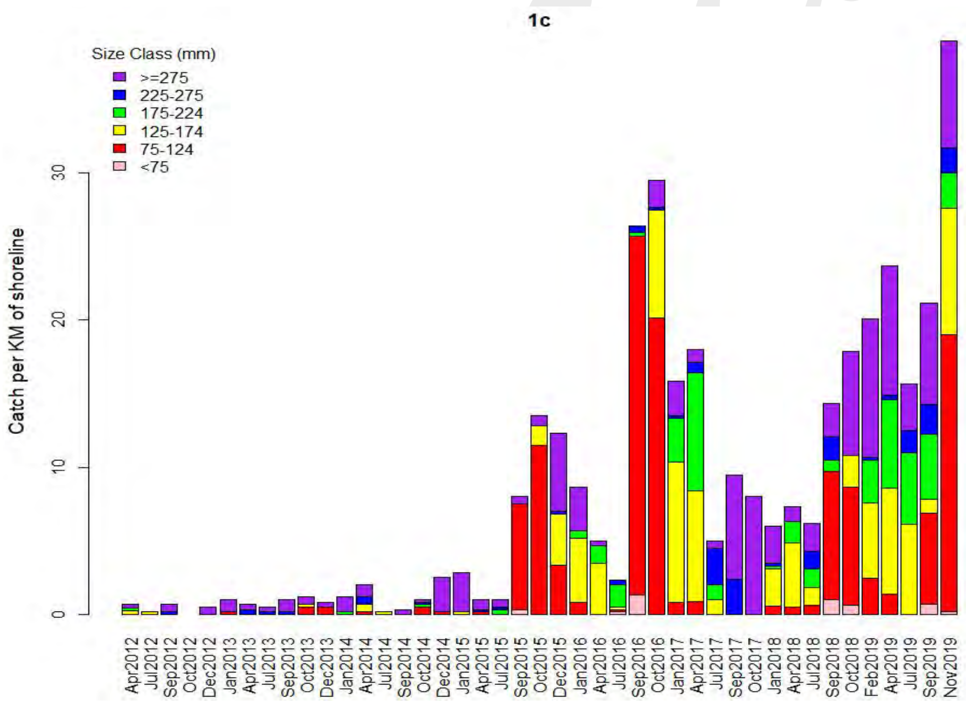

Figure 1. Brown trout seasonal catch rates (number of fish caught per km of shoreline) are based on electrofishing in Reach 1C, Glen Canyon, AZ. Size classes are assigned by fork length and abundances were computed for each of six size classes (<75 mm, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and >=275 mm FL) based on catch-per-unit-effort (CPUE, km per shoreline) for electrofishing. Brown trout CPUEs are based on data from the 1st pass of a multiple-pass mark-recapture TRGD study.

Therefore, it is essential that the influence of different types of flows in the selected ROD alternative be evaluated on behalf of both rainbow trout and brown trout in the FY2021-23 TWP. The project elements proposed herein are driven by six overarching research questions that apply to both rainbow and brown trout.

1) What are the effects of TMFs on trout survival, recruitment, growth, and dispersal?

TMFs are designed to limit recruitment by stranding YOY trout in low angle habitat. A presentation was provided to the GCDAMP Technical Work Group (TWG) (Korman, 2019) regarding the key uncertainties of TMFs, which include limits 1) in scientists' ability to accurately forecast recruitment, and 2) flow design components (i.e., maximum peak discharge of the TMF cycle, time interval between max flow level and beginning of flow recession, downward ramp rate, minimum discharge level, number of TMF cycles per year, triggering mechanisms). Although reducing some of these uncertainties is the most sensible strategy, the ideal circumstances for implementing TMFs occurs infrequently (e.g., 2011 equalization year), and therefore, evaluating actual population-level effects of TMFs can only be determined by doing them. Consequently, a literature review on fish stranding will be finalized in 2020 to better inform managers responsible for implementing flow related components (i.e., flow magnitude, duration, down-ramp, diel period, and minimums) associated with the design of TMFs. Since it is unclear the extent to which TMFs will reduce recruitment, this project broadly focuses on the following questions: 1) what proportion of total recruits are vulnerable to stranding and mortality in low angle shorelines, 2) what is the relationship between aerial coverage of low angle shoreline and discharge levels, 3) will survival rates of YOY trout increase following a TMF, thereby partially or fully compensating for direct losses of trout during the TMF, 4) are rainbow trout and brown trout equally susceptible to TMFs, and 5) will TMFs unexpectedly trigger a downstream dispersal event? Therefore, we propose to monitor YOY trout survival, recruitment, growth (Project Elements H.1, H.2), and downstream dispersal (H.2, Project G) in years with and without TMFs to address these critical uncertainties.

2) What are the effects of spring and fall HFEs on trout recruitment, dispersal, and growth?

An increase in rainbow trout growth rates and recruitment of YOY in Glen Canyon was observed following the 2008 spring HFE, and as an effect was attributed to an increase in food availability (Korman, 2011a). However, it is uncertain whether future spring HFEs will produce a similar response because the 2008 observation was a single, unreplicated event and antecedent conditions at the time of the spring HFE may have been unique (e.g., low trout abundance, higher nutrient availability due to large inflows to Lake Powell). Therefore, if spring HFEs are implemented, ecosystem responses will be evaluated using the current TRGD sampling program as modified by the reduction in sampling effort in this work plan to one sub-reach (Project Element H.2). The effects of fall HFEs on rainbow trout in Glen Canyon are uncertain even though there have been six fall HFEs conducted to date (2004, 2012–2014, 2016, 2018).

Mark-recapture data from the NO (FY2015-17) and TRGD (FY2018-20) projects clearly show that fall HFEs have not led to increased downstream movement (Korman and others, 2016). Additionally, there is some indication that fall HFEs can reduce growth rates of adult trout during late fall and winter in some years (e.g., 2014) but not in others (e.g., 2016), but results are confounded by strong interannual and seasonal variation in trout growth (Yard and others, 2016; Yard and Korman, 2020).

There have been a number of hypotheses proposed for the expansion of brown trout in Lees Ferry (Runge and others, 2018), one of which is that fall HFEs cleanse spawning gravels immediately prior to brown trout spawning thereby improving egg survival and recruitment. Comparisons of brown trout recruitment made between years with and without fall HFEs would suggest that fall HFEs do not appear to be presently facilitating reproductive success or recruitment the following year (Yard and Korman, 2020). Therefore, additional monitoring of trout growth and other extrinsic factors before and after fall HFEs may resolve uncertainties about the effects between species and on overall trout growth. Further, evidence indicates fall HFEs reduce adult fish growth during fall and winter, which in turn reduces their rate of sexual maturation and fecundity (Korman and others, 2017). Therefore, additional monitoring is proposed to examine how adult growth following a fall HFE influences sexual maturation, fecundity, and, by extension, recruitment the following year (Project Element H.2).

3) What controls the number of trout that disperse from Glen Canyon into Marble Canyon, and the quantity reaching the LCR?

The LTEMP model used to simulate rainbow trout movement from GCD to the LCR assumed that trout dispersal was a constant proportion of recruitment, and that trout residency in Marble Canyon was constant through time (U.S. Department of Interior, 2016a). The NO and TRGD data support the first assumption, but not the second. In 2017, rainbow trout had the largest recruitment year since 2011 (equalization flow period). This same year, sizeable numbers of YOYs appear to have immigrated into Marble Canyon. Immigration of trout to the LCR reach appears to be a two-step process, initially as a short-duration dispersal of YOYs from Lees Ferry to upper-middle Marble Canyon in their first summer, followed by a downstream dispersal of longer-duration from Marble Canyon to the LCR (Korman and Yard, 2020). Basically, when higher recruitment occurs in Lees Ferry it ultimately leads to higher numbers of young rainbow trout dispersing downstream into Marble Canyon (Korman and others, 2016).

Over the following years since the large recruitment event in 2017, rainbow trout abundance increased in Glen Canyon, and with higher trout densities the trout population has started to show a declining trend in condition factor and sexual maturity for larger sized fish, and by extension, has resulted in reduced recruitment. In addition, 2017 appears to have been the poorest recruitment year for brown trout.

We are uncertain why this poor recruitment year occurred; however, one hypothesis is that there might have been negative interspecific interaction between rainbow trout and brown trout resulting in interference on brown trout spawning bars. Nevertheless, brown trout appear to be growing and surviving better than young rainbow trout and it remains uncertain whether they too will demonstrate similar downstream dispersal once their parental population becomes larger.

Collectively, these data indicate that 1) large numbers of YOY rainbow trout disperse from Glen Canyon to the upper and middle portions of Marble Canyon in the summer and fall, 2) trout in Marble Canyon then become the source of trout at the LCR over the next 1-5 years (Korman and others, 2016; Korman and Yard, *unpublished data*), and 3) prolonged conditions with clear water and high nutrients will maintain large populations of trout in Marble Canyon which in turn will lead to longer periods of high trout abundance at the LCR (Korman and others, *in review*). Therefore, we propose to continue evaluating rainbow trout and brown trout dispersal out of Glen Canyon and monitoring trout population dynamics in Marble Canyon and near the LCR confluence in conjunction with humpback chub monitoring (Project Element H.2, Project G).

4) What factors control the quality of the rainbow trout fishery?

The quality of the Lees Ferry trout fishery depends on growth rates of rainbow trout and the number of juvenile trout that recruit into the adult population, which are then targeted by anglers. The LTEMP trout model assumed that fish growth was inversely related to trout density, and that flow was the only factor that influenced recruitment (U.S. Department of Interior, 2016a). More recent findings indicate that greater food availability during the spring and summer leads to better growth of juvenile rainbow trout and higher recruitment (Yackulic, *unpublished data*). There is also increasing evidence that nutrient availability (specifically SRP) plays an important role in recruitment and adult trout growth by increasing the production of invertebrate prey, or when trout densities are at or the below carrying capacity as was observed in the years following the 2014 rainbow trout population crash (Yackulic, 2020; Korman and others, *in review*).

There is seasonal variability in rainbow trout condition factor for large sized fish (> 300 mm FL) (Korman and others, 2017). Reduced condition likely led to decreased survival of larger sized fish and ultimately reduced rainbow trout abundance in the Lees Ferry trout fishery. Notably, relative condition factor for brown trout is much higher than rainbow trout (2015-2019), particularly in the fall just prior to the spawning period (November-January), which is the season that rainbow trout appear to be the lowest in condition. Comparisons of length-weight relationships between trout species indicate that rainbow trout display a negative-allometric growth relationship, suggesting an overall decrease in growth or an elongation in length without a commensurate increase in weight (Yard and Korman, 2020).

These findings identify deficiencies in the LTEMP trout model because they indicate that 1) factors other than flow can have more important effects on trout recruitment, and 2) interannual and seasonal variation in nutrients may be a more important determinant on trout growth than density as was assumed in the LTEMP model. Resolving this uncertainty about trout growth is critical to managing the Lees Ferry fishery.

Therefore, we propose to continue studying trout growth and recruitment in relation to both top-down and bottom-up factors such as fish density and biomass, nutrient availability, and the prey base to identify key factors that promote a high quality trout fishery in Lees Ferry (Project Elements H.1, H.2, H.3, H.4, Projects F, E).

5) Why are young brown trout (< 75 mm FL) not as susceptible to capture by electrofishing earlier in the year?

Typically, brown trout spawn from November-January while rainbow trout mostly spawn from March-April, thus it follows that the early life history stages (hatch and swim-up) 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 sampling effort as would be expected based on their earlier spawning time. Instead juvenile brown trout are not readily caught until 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 YOY brown trout are not occupying the near shoreline (wetted edge) when smaller in size. If YOY brown trout are using different habitat at smaller sizes (<75 mm FL), they are not likely to be as affected by experimental flows. There are several possible explanations for the seasonal difference in juvenile brown trout catch, these

1) misidentification of species at early life history stages,
2) limited vulnerability due to low fish densities and spatial heterogeneity, and
3) differences between trout species in habitat use at early life history stages.

Nevertheless, seasonal differences in catch vulnerability of juvenile brown trout could have significant implications on the efficacy of using late spring TMFs or other experimental flows as management actions. Therefore, to resolve some of the uncertainties about seasonal differences in vulnerability between the two juvenile trout species we propose to implement a Brown Trout Early Life Stage Survey (BTELSS) (Project Element H.3) while continuing to monitor and quantify brown trout abundance, growth, and survival by following the recruitment of YOY into the sampleable population (Project Elements H.1, H.2).

6) What factors regulate brown trout population dynamics in Glen Canyon, and if control measures are implemented, what is the efficacy of those management actions?

As mentioned above, it is unclear what factors led to the recent increase of brown trout abundance in Lees Ferry. The efficacy of various flow and non-flow control options for controlling brown trout abundance is also uncertain. Runge and others (2018) examined the likely efficacy of several potential management interventions to reduce brown trout, followed by analyzing the effects of those interventions on other resources of concern. They identified some removal strategies that may be effective in moderating population growth in brown trout, including mechanical removal, TMFs, seasonal timing of high flows, and incentivized harvest using anglers to target larger size classes. Currently, the NPS Glen Canyon National Recreation Area (GCNRA) intends on implementing an incentivized harvest of larger-sized brown trout in the fall of 2020. The management goal is to reduce brown trout abundance by approximately 50% by the removal of 2,000-4,000 animals per year. The efficacy of this incentivized harvest is unknown and will therefore need to be quantified by comparing: 1) annual harvest outcomes to population estimates, and 2) proportions of PIT-tagged fish caught and removed to estimated tagged animals available to capture. The efficacy of incentivized take will use mark-recapture methods to estimate abundance and vital rates (survival, growth, recruitment) as well as tag-retention estimates for brown trout to inform future management actions (Project Elements H.2, H.4, J.2). This will require information from anglers on brown trout removals (i.e., quantity, recapture, size, and location).

5. Proposed Work

5.1. Project Elements

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

David Rogowski, Fish Biologist, Arizona Game and Fish Department

The fish community downriver of GCD has been monitored by AGFD using electrofishing methods since the early 1980s (Maddux and others, 1987), and since 1977 using angler surveys. Monitoring of the fish population via electrofishing was standardized in 1991. The long-term monitoring program is designed to detect population level changes in the rainbow trout fishery utilizing minimal sampling and has provided long-term trend data used to manage the rainbow trout fishery (McKinney and others, 2001; Makinster and others, 2011). This program underwent refinements following PEPs in 2000, 2009, and 2016 (Anders and others, 2001; Bradford and others, 2009). The 2016 PEP recommended continuing to collect long-term trend data in Lees Ferry (this project) while also incorporating mark-recapture methods into the sampling design to estimate vital rates (Project Element H.2).

The objective of this project is to track the status and trends of rainbow trout in the Lees Ferry reach of the Colorado River and to continue gathering long-term trend data on trout relative abundance, size composition, distribution, and recruitment as well as angler satisfaction and catch quality. As such, this project provides data that directly informs management decisions within the Recreational Experience and Rainbow Trout Fishery LTEMP resource goals; however, sampling also indirectly provides data information on the status of the Other Native Fish and Non-native Invasive Species resource goals.

These resource goals are listed below:

- ***Recreational Experience.*** Maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.
- ***Rainbow Trout Fishery.*** Achieve a healthy high-quality recreational rainbow trout fishery in GCNRA and reduce or eliminate downstream trout migration consistent with NPS fish management and ESA compliance.
- ***Nonnative Invasive Species.*** Minimize or reduce the presence and expansion of aquatic nonnative invasive species.

We propose to conduct three sampling trips per year (spring, summer, and autumn) to assess the status and trends of the fish population using CPUE metrics. During these trips, 40 sites will be sampled using a random stratified design based on subreaches (upper, middle, lower). All fish captured will be identified, measured, and when feasible weighed (≥150 mm total length; TL). Rainbow trout >150 mm TL and brown trout >75 mm TL will be tagged with passive integrated transponders (PIT) for mark-recapture studies investigating movement, growth, and apparent survival rates. One night of sampling in the summer and autumn monitoring trips will focus on the detection, status, and population trends of rare nonnative species including brown trout in Glen Canyon (Project Element I.2). Targeted sampling for rare nonnatives in conjunction with normal summer and autumn monitoring efforts will provide the opportunity to rapidly respond to new aquatic invaders.

In addition to the proposed monitoring using standardized electrofishing methods, we will conduct angler creel surveys to estimate angler effort, catch, and harvest on an annual basis. AGFD angler creel surveys began in 1977 and have continued since then, becoming standardized in 2011. Creel surveys will be scheduled on a monthly and weekend/weekday basis to allocate survey effort relative to angling effort during the year. These interviews will be conducted near the boat ramp for anglers fishing in the upriver section (between GCD and the Lees Ferry boat ramp) and in the walk-in section (from the Lees Ferry boat ramp downstream below the Paria River).

The angler surveys provide data on angler catch rate, including angler estimates of fish ≥ 14” and fish ≥ 20” in length, and the number and size of harvested fish. Angler estimates do not provide accurate length information associated with the catch, thus AGFD cannot accurately assess whether goals related to angler catch quality are being met with our normal creel surveys. Therefore, we propose to continue a citizen science project to assess whether goals related to angler catch quality are being met by utilizing fishing guides as well as citizen anglers to collect length data on fish captured. Participating guides will measure fish caught by clients on randomly selected (to the extent practicable due to guiding schedules) weekend days and weekdays and may be paid ~$10/day for participating.

We are also enrolling citizens that frequently fish Lees Ferry in the citizen science project to gather more data. Guides and anglers will measure all fish caught in a day to ensure a representative sample. Exact numbers of guides and days will depend on guide interest and desired sample size.

Project Element H.2. Experimental Flow Assessment of Trout Recruitment

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Kimberly Dibble, Fish Biologist, U.S. Geological Survey, GCMRC
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Clay Nelson, Fish Biologist, U.S. Geological Survey, GCMRC
Molly A.H. Webb, Research Fishery Biologist, Bozeman Fish Technology Center, USFWS
James A. Crossman, Fish Ecologist, BC Hydro, Vancouver, Canada

This research is referred to as the Trout Reproductive and Growth Dynamics (TRGD) Project, and is designed to determine the effects of LTEMP ROD flows on the recruitment of YOY rainbow trout and brown trout in Glen Canyon, the growth rates of juvenile and adult trout, 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 (e.g., trout density and recruitment, prey availability, nutrients, etc.) that control the abundance and growth of the Glen Canyon trout populations. This improved understanding could lead to the identification of policies other than flow manipulation that could benefit the Lees Ferry fishery and limit the downstream dispersal of rainbow trout to the LCR, as well as controlling brown trout should this species become even more established in Glen Canyon.

Specifically, the proposed project will evaluate:

1) The effects of higher flows in spring and summer during equalization events, and potentially more stable flows (i.e., ‘Bug Flows’) in summer on trout recruitment, growth, and dispersal.

2) The effect of fall HFEs on recruitment of trout in Glen Canyon, measured either through direct effects on juvenile survival or through reduced egg deposition in later years driven by reduced growth of trout (which reduces fecundity and rates of sexual maturation).

3) The effect of spring HFEs on trout recruitment, growth, and dispersal.

4) The effect of TMFs on rainbow and brown trout recruitment and dispersal.

5) Sexual maturation

6) Monitoring downstream trout dispersal (YOY) and population dynamics at the LCR reach.

Fieldwork and Population Models

The sampling design is specific for conducting seasonally based mark-recapture studies, data that are then used independently to inform 1) a spatially-stratified open population model for rainbow trout (Korman and Yard, 2017; Korman and others, 2017), and 2) a population model for brown trout (Yackulic, 2020; Project Element H.4). For purposes of study replication, a multi-reach mark-recapture sampling design was established in the FY2018-20 TWP having three sub-reaches from Glen Canyon Dam to Lees Ferry, each with an assigned 3-km length. This sampling design will continue in FY2021, but due to budget constraints only one sub-reach will be sampled starting in FY2022. Sub-reaches contain a combination of low-angle (spawning bars and possible stranding habitat) and high-angle (talus slopes) shorelines and are located in the upper, middle, and lower portions of Glen Canyon. The lowest sub-reach (1C) has been sampled since 2012 (Figure 2), 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 NO Project (2012-2017; FY2015-17 TWP) and more recent work plans (FY2018-20 TWP). Four TRGD trips and one hybrid June trip (associated with JCM, Project G) are proposed annually in this work plan.

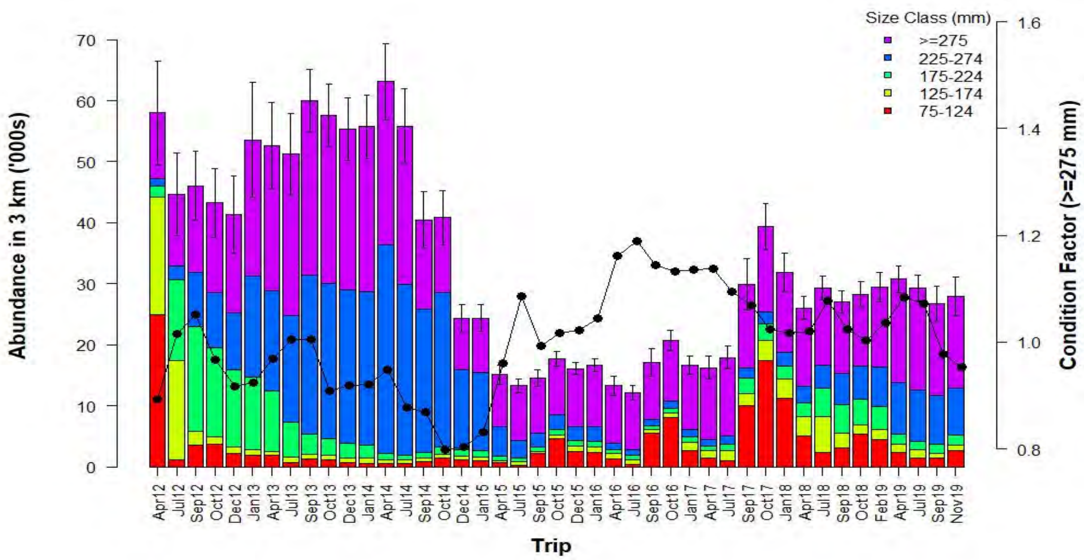

Figure 2. Size-stratified abundance estimates for rainbow trout in Glen Canyon Sub-reach 1C. Size classes are assigned by fork length (FL) and abundances were computed for each of five size classes (75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and >=275 mm FL) based on mark-recapture using electrofishing. The 2nd axis represents the trend in relative condition across time.

Equalization, Fall-HFEs, and Spring Power Plant Capacity Flows

Growth rates (in weight) are one of the more sensitive biotic variables to assess trout population response to experimental flows, particularly for large-sized fish because of their higher metabolic costs and feeding limitations potentially brought about by flow disturbances to the food base. Monthly growth rates for the time intervals between October-January and January-April will represent the post-fall HFE growth in years when fall HFEs are conducted, whereas growth over those same time intervals when HFEs are not conducted will form the experimental controls to make the necessary contrasts. Similarly, growth rates for time intervals between April-September will be used to assess flow effects following spring HFEs or spring power plant capacity flows, as well as stable higher flows versus flows of a lower magnitude. Additionally, other demographic changes such as YOY abundance will be used to assess flow effects on annual recruitment and dispersal of YOY across years. Regardless of the experimental flow being tested, many replicates across years and sub-reaches for each of the demographic variables (abundance, growth, biomass, movement, and survival) are required in order to make informed inferences about these experimental flows, particularly since prior antecedent conditions (condition factor and sexual maturity) are likely to be influencing trout responses at a population level.

The analytical approach we intend to use will require some additional years of data collected with and without flow treatments to determine how trout (rainbow trout and brown trout) dynamics in Lees Ferry respond to weekend stable flows (Bug Flows) designed to improve aquatic insect egg survival during spring and summer. Late-spring and summer trout growth will be used as the primary parameter to make comparisons and contrasts as the trout population responds to flow effects between years.

Sexual Maturation

We have shown that condition factor of rainbow trout in the fall is a good predictor of an index of sexual maturation rates the following winter and spring (Yard and Korman, 2020). Condition factor is higher when growth is higher, potentially leading in turn to an increase in the proportion of trout that reach sexual maturity and spawn. Preliminary data from the FY2018-20 TRGD project show that annual recruitment is well predicted by both 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 responding to large recruitment events. Current methods to evaluate sexual maturity rate in the field are relatively crude, relying on estimates of the proportion of fish that express gametes when manipulated. This approach is known to lead to a substantial bias in sex ratios (i.e., males express gametes more readily than females), and it is the uncertainty of whether or not the percentage of males or females expressing gametes each year is proportional to the actual percentage of adults that spawn and contribute to recruitment. In FY2018-20 we began a more detailed sexual maturation study based on direct examination of gonadal structures via ultrasound, dissection, and histology working in cooperation with reproductive biologists Drs. Molly Webb and James Crossman.

We propose to continue this work in the FY2021-23 TWP, which will include development of a reproductive staging key so that reproductive state for sampled individuals can be reliably determined in a repeatable fashion. Histology provides a reliable method of quantifying reproductive state which can then be compared to classifications based on ultrasound and our traditional gamete expression method. Histological results from samples collected to date are concerning, which indicates that some of the larger trout that should be sexually distinct, are not. Further, a surprisingly large proportion of adult fish are not sexually mature. We suspect these patterns are the result of low growth rates due to limited prey availability and high levels of competition. The proposed work will provide insight on the extent to which trout growth influences the reproductive stages and its effects on recruitment. Two primary publications will be produced from this work. The first will focus on the reproductive key and comparison of methods used to assign reproductive state and maturity levels.

This paper will determine whether our standard method of evaluating reproductive state (expression of gametes) is sufficient in scope or whether more time-consuming methods (histology) are required. A second paper will evaluate the effects of growth and condition on the reproductive state of trout based on contrasts made across years (2019-2023) and seasons (fall, winter, spring).

Trout Management Flows (TMFs)

TMFs were intended to be tested early in the LTEMP implementation period (if warranted); however, there are some critical information needs required perhaps before TMF implementation, such as flow duration, magnitude, timing, frequency, and fish responses to antecedent conditions. Concerns were raised in the FY2018-20 TWP about the best TMF flow design. The central issue was why have in place a sampling design to study effects of TMFs in advance of addressing the questions raised in the LTEMP ROD about experimental flow design (Section 2.2.1 Alternative D). Recognizing this concern, an extensive literature review on trout stranding is currently being conducted. Findings from this will be synthesized, and a report will be provided to managers on possible flow characteristics that may be helpful in the design of an experimental TMF. It remains uncertain whether management agencies will implement a TMF during future years, but if a TMF is implemented, data from the TRGD project will be used to evaluate trout survival, abundance, and dispersal in response to this type of experimental flow.

Monitoring Downstream Trout Dispersal and Abundance at the LCR

The abundance and persistence of rainbow trout near the LCR depends on both the numbers of juvenile trout that disperse from Glen Canyon, and their subsequent survival and reproduction rates in Marble Canyon (Korman and others, 2016). Another key objective of this program is to reduce the downstream dispersal of YOY trout from Glen Canyon into Marble Canyon. It is likely that small trout move downstream and repopulate Marble Canyon during years when the Lees Ferry fishery has large recruitment events (Yard and Korman, 2017). The downstream movement of small trout appears to be governed by high densities and growth conditions in Glen Canyon (Yard and others, 2016; Korman and others, *in review*). It is critical to quantify downstream dispersal under both TMF and non-TMF years to determine if this objective is being met. The House Rock reach (17.3-19.5 river miles downstream from Lees Ferry) rarely detects YOY trout in the electrofishing catch because channel morphology and hydrology are not considered suitable for trout reproduction. Similar data from 2016 from the NO research showed no YOYs in upper and middle Marble Canyon in July but significant numbers in September. In contrast, YOYs were abundant in Glen Canyon on both July and September trips.

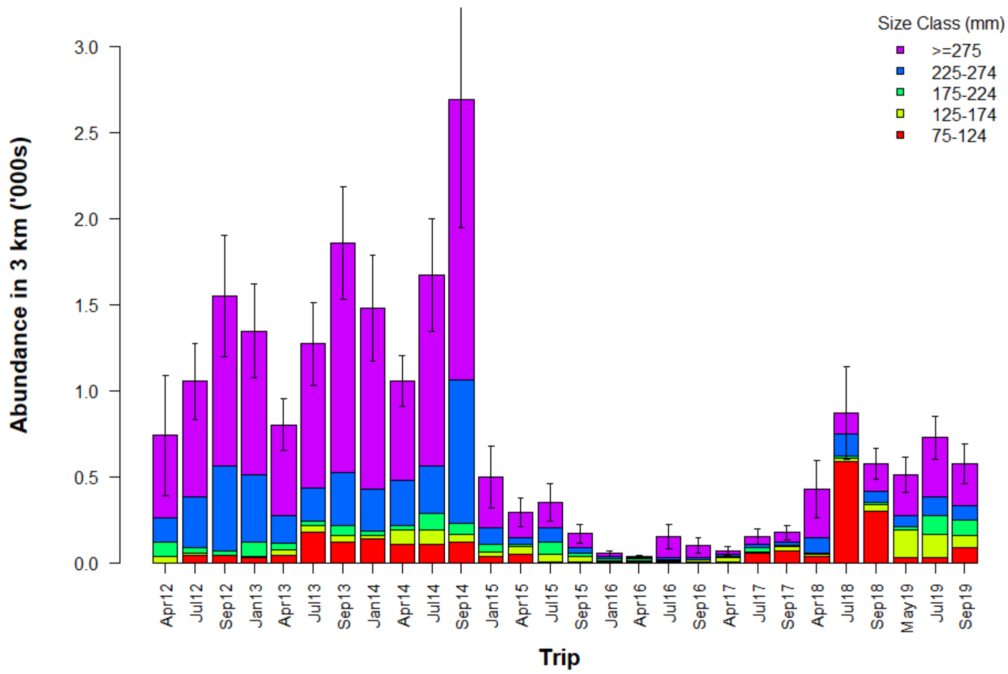

Figure 3. Seasonal abundance estimates (number of fish caught per km of shoreline) for the rainbow trout population located below the confluence of the Little Colorado River (SubReach IVb). Size classes are assigned by FL and abundances were computed for each of five size classes (75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and >=275 mm) based on mark-recapture using electrofishing.

This pattern shows that movement of YOYs from Glen Canyon occurred in 2016 sometime between July and September. This reach is therefore ideal for monitoring the influx of recruits migrating to and repopulating Marble Canyon. This provides a means to test the assumption underlying the LTEMP model that trout recruitment and downstream dispersal correspond with YOY recruit densities. This can be accomplished relatively easily based on a comparison of length frequencies in Glen Canyon and Marble Canyon on July and October JCM trips (Project Elements G.3 and G.6). This design is very similar to what was done under the NO project. Growth between April-July trips and July-October trips will be used to quantify conditions during the high growth period which are potentially affected by spring HFEs, TMFs, and inter-annual trends in nutrient concentrations in flow from GCD. Growth over these periods in years when such flows are conducted can be compared to those when they are not. The additional logistical cost is not included in this proposal but is identified here due to the linkage between this project element and the JCM studies (Project Elements G.3 and G.6) (Figure 3).

Project Element H.3. Brown Trout Early Life Stage Survey in Glen Canyon

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Clay Nelson, Fish Biologist, U.S. Geological Survey, GCMRC

The brown trout population in Glen Canyon has increased rapidly in recent years, such that experimental flows and incentivized harvest are being considered as management options to decrease the risk of this species to endangered humpback chub populations in downstream reaches. The LTEMP and its associated ROD identified flow manipulation as a potential tool to regulate rainbow trout recruitment, but we lack early life stage information for brown trout to understand the species' basic biology, nearshore habitat use, and its potential vulnerability to experimental flow manipulation. As such, the Brown Trout Early Life Stage Survey (BTELSS) objectives are to 1) understand early life stage vital rates for YOY brown trout in Glen Canyon, 2) assess hatch and swim-up dates to identify when brown trout are likely to be emerging from gravel redds, and 3) identify habitat preferences for low angle (cobble bars, vegetated sand bars, debris fans) vs. high angle (talus) nearshore habitat to understand stranding vulnerability to experimental flows, including TMFs. This research will help fill basic but critical information needs pertaining to brown trout early life-history stages to inform management options for the expanding brown trout population in Glen Canyon.

In previous workplans (FY2011-12, FY2013-14, FY2015-17), the Rainbow Trout Early Life Stage Survey (RTELSS) mounted an extensive effort to understand early life stages of rainbow trout by collecting data on vital rates and redd distribution and by monitoring the response of YOY trout to various experimental and non-experimental flows in Glen Canyon. These included nonnative fish suppression flows (2003–2005), equalization flows (2011), and multiple spring and fall HFEs (2008, 2011-2014, 2016) (Avery and others, 2015; Korman and others, 2011a, b). Vital rate data provided a more mechanistic understanding of downstream emigration events and population-level changes in adult rainbow trout in Grand Canyon (Korman and others, 2012; Melis and others, 2012). Although the RTELSS program provided useful information pertaining to the response of YOY rainbow trout to flow manipulation, this information is not necessarily analogous to brown trout since they have differing life history cycles and may be utilizing different habitats during early life stages.

The BTELSS project focuses on early life history stages of brown trout that are often too small developmentally to be captured using conventional sampling methods (Project Element H.2). Typically, brown trout spawn over a three-month period (November-January) in advance of rainbow trout (March-April), so the early life history stages 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 YOY brown trout are not occupying the near shoreline (wetted edge) when smaller in size, as rainbow trout do. If YOY brown trout are using offshore habitats at smaller size classes, they are not likely to be as affected by experimental flows such as TMFs, particularly in the spring when they are most vulnerable to changes in flow.

BTELSS sampling will be conducted monthly (January-May) to determine brown trout hatch date distribution, hatch success and early survival, daily incremental growth, and relative densities across the late winter and spring months (Campana, 1992; Korman and Campana, 2009; Stevenson and Campana, 1992). The BTELSS study design will resemble that from previous RTELSS work, with at least 20 sites sampled per trip via a combination of backpack and boat electrofishing, with sites equally distributed between low and high angle nearshore habitat types. Sampling sites approximately 30-50 m in length will extend 3-4 m from shore and will be fished in an upstream direction (backpack electrofishing) and in a downstream direction (boat electrofishing).

However, unlike the RTELSS study design, where sampling sites were distributed across low and high angle habitats from Glen Canyon Dam to Lees Ferry, sites in the BTELSS project will be located within the three (3-km) sites established in the TRGD project (Project Element H.2) to facilitate comparison among data sources in FY2021, when TRGD sampling is still occurring in those three sub-reaches. Sites will be sampled at daily minimum flow following the ‘low’ tidal wave from the dam (~12 am) to Lees Ferry (~6 am). At each site, all brown trout identified will be anesthetized with clove oil, measured to the nearest mm, and pit-tagged if >75 mm FL to assist with marks needed for the TRGD project (E.2). Most brown trout will be released to their original sites, but 1-2 fish distributed across multiple size classes at each site will be frozen on ice and brought back to the laboratory for otolith removal and microstructural analysis to assess hatch and emergence dates. This combination of field and laboratory data can be used to inform the eventual design of TMFs or other flows targeted for brown trout eradication.

Specimens collected for the otolith microstructural work proposed in Project Element H.3 will minimize loss of life to the extent practicable per Tribal concerns. While the fish collected will be too small to put toward beneficial use at the aviary or for human consumption, we propose to return what remains from each fish back to the Colorado River to nourish other components of the ecosystem.

Project Element H.4. Salmonid Modeling

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Kimberly Dibble, Fish Biologist, U.S. Geological Survey, GCMRC

The goal of this element is to analyze data on salmonid populations collected in other elements to estimate the efficacy of ongoing management actions and improve our capacity for predicting impacts of future management actions.

Specifically, we identify four areas of research in this workplan: 1) reassess the causal hypotheses explored in Runge and others (2018) using data collected in recent years, 2) estimate the efficacy of incentivized harvest of brown trout by modifying the existing brown trout model to incorporate harvest data to inform managers and improve design of incentives (Project J), 3) estimate population dynamics of rainbow trout in the Lees Ferry reach in response to experimental flows and other drivers, and 4) continue development of a simple integrated model to predict recruitment and outmigration of rainbow trout using multiple data sources over nearly a 20-year period.

When Runge and others (2018) was published, brown trout data were relatively sparse and there was substantial uncertainty regarding basic demography and causal hypotheses. For example, based on a synthetic analysis of vital rates (reproduction, survival, and growth) it was estimated that there was a 50% probability that brown trout would continue to increase in the future. With additional mark-recapture data and subsequent improvement in our estimates of vital rates, recent analysis suggests >99% probability that brown trout populations will continue to increase in the foreseeable future in the absence of changes to management. In addition, actual adult brown trout abundances continue to trend upwards (Figure 4). While it is doubtful that uncertainty in causal hypotheses has declined to the same extent as uncertainty in basic demography, we nonetheless believe it is important to reassess causal hypotheses during this workplan using new data and propose a reanalysis. In particular, recent improvements in our understanding of reproduction in rainbow trout may allow us to better quantify the extent of interference competition in different years.

Estimating the impact of incentivized harvest on the population growth rate and overall abundance of brown trout is essential for judging the efficacy of this management action, designing incentives, and determining whether additional management actions are required. We have continued to modify the integrated population model developed to support the Runge and others (2018) analysis to incorporate additional data and relax assumptions that were necessary when data were sparser. Estimating the impacts of incentivized harvest will require additional modifications that depend on how well harvested brown trout are monitored (i.e., the extent to which PIT tags are recovered and whether the general locations of removals and rough size classes of individuals are known). We plan to work on these modifications over the course of the FY2021-23 TWP.

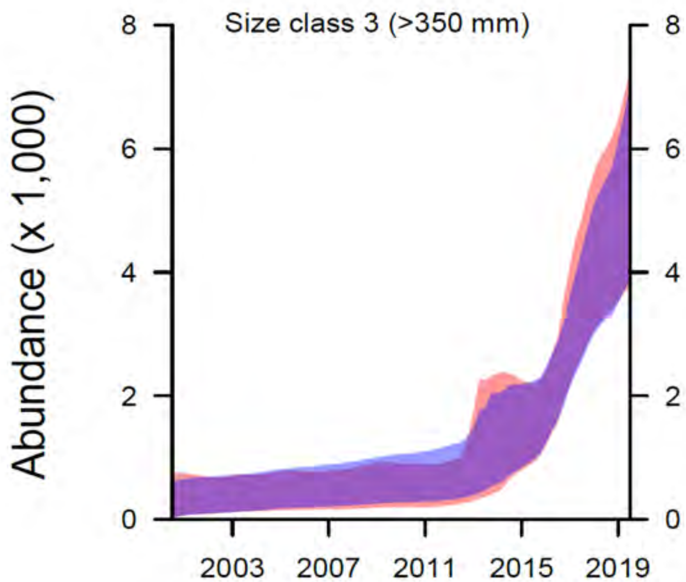

Figure 4. Population trajectory of the adult brown trout (>350 mm) population in Glen Canyon using data from 2001-2019 (Yackulic, 2020).

The ability to estimate rainbow trout population dynamics relative to management alternatives outlined in the LTEMP BiOp (U.S. Department of the Interior, 2016c) is important for effective management of multiple resources in the CRe and was the motivation for the original TRGD design (Project Element H.2). Flow alternatives outlined in LTEMP include TMFs, HFEs and Bug Flows, which may directly or indirectly affect the rainbow trout population in Lees Ferry. We propose to continue to estimate rainbow trout growth, survival, and reproduction in the Lees Ferry reach and relate it to ongoing flow experiments.

In addition, we plan to continue development of a rainbow trout recruitment and outmigration model that integrates data from various projects over the last two decades. The recruitment part of this model was initially developed using data from 2001 to 2016, and suggested that nutrients (SRP) in dam releases and existing rainbow trout population size were much better predictors of recruitment than the flow model used in the LTEMP EIS, which was based on a previous stock assessment. Nonetheless, it always possible that a significant statistical relationship will fade over time, so in the FY2018-20 TWP we used estimates from the 2001-2016 period to predict recruitment in 2017-2019 and formally compared predictions from the SRP and flow models to estimate recruitment (Figure 5).

This process allows for continual updating of the weight of evidence for various hypotheses and is the basis of programs that use more formal adaptive management (e.g., mallard management). Even if we assumed equal support for the flow and SRP models in 2016 (i.e., ignore the weight of evidence in the 2001-2016 data and only use the parameter estimates), formal comparison of predictions to observations suggests the SRP is 4 times more likely than the flow model to predict rainbow trout recruitment. In the FY2021-23 TWP, we propose to continue to modify this model to estimate interannual variation in outmigration and test hypotheses about drivers of outmigration. These modifications were a goal in the FY2018-20 TWP that was not met due to underfunding and redirection of effort to brown trout, however, we hope to complete this work so as to provide better predictions of the potential impacts of management actions in Lees Ferry on downstream resources – especially humpback chub around the LCR.

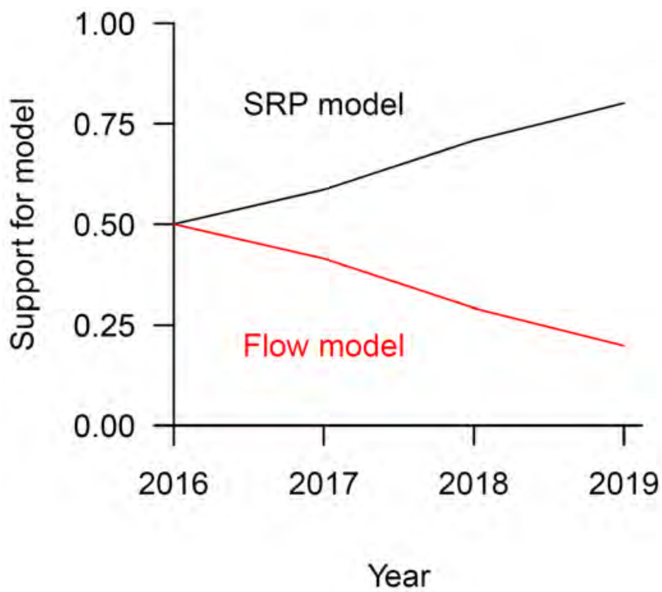

Figure 5. Modeling of rainbow trout recruitment that suggests that soluble reactive phosphorous (SRP) in dam releases and existing rainbow trout population size are better predictors of recruitment than the flow model used in the LTEMP EIS.

5.2. Outcomes and Products

Project Element H.1.

Outcomes:

- Metrics on long-term trends in the rainbow trout fishery such as relative condition, relative density, growth, and recruitment, and the distribution and abundance of nonnative species. Metrics on the angling experience for both boat and walk-in anglers, including relative angler use, angler catch per unit effort values, and a rating of the fishery. AGFD angler surveys also provide information for Project J.

Products:

- Annual Report, and one anticipated peer-reviewed publication during this workplan. Presentations will be given at the Annual Reporting meeting and at regional meetings.

Project Element H.2.

Outcomes:

- Evaluate how experimental flows influence recruitment, growth, survival, and dispersal of rainbow trout and brown trout in Glen Canyon.

Products:

- Peer-reviewed journal article(s), presentations at the GCDAMP Annual Reporting Meeting and at other scientific meetings. These journal articles include two manuscripts on the reproductive physiology of trout in Glen Canyon. Provision of annual summaries of state variables and vital rates at the GCDAMP Annual Reporting Meeting and to the TWG and other stakeholder groups, if there is additional interest in further evaluating the response of trout to any combination of LTEMP flow experiments.

Project Element H.3.

Outcomes:

- Evaluate brown trout early life stage vital rates, hatch and swim-up dates, and habitat preferences in Glen Canyon to better understand brown trout vulnerability to experimental flows.

Products:

- Peer-reviewed journal article, presentation(s) at Annual Reporting Meetings and at other scientific meetings.

Project Element H.4.

Outcomes:

- Analyze data and develop models for salmonid populations to estimate the efficacy of ongoing management actions and improve capacity to predict impacts to fish populations from future management actions.

Products:

- Peer-reviewed journal article(s), presentations at Annual Reporting Meetings and at other scientific meetings related to brown trout population abundance, efficacy of the NPS incentivized brown trout harvest program, rainbow trout population dynamics as related to experimental flows and other drivers, and integrated models to predict rainbow trout recruitment and outmigration.

5.3. Personnel and Collaborations

The overall project leads for Project H are Dr. Michael Yard, a Fish Biologist at GCMRC who specializes in rainbow trout population dynamics, statistical modeling, and complex sampling designs and Dr. Kimberly Dibble, a Fish Biologist at GCMRC with expertise in fish physiology, otolith microstructural analysis, and metadata analysis. Dr. Charles Yackulic is a Research Statistician at GCMRC specializing in population dynamics with an emphasis in modeling linkages and vital rates between trout populations. Dr. Josh Korman is a Fish Biologist with Ecometric Research, Inc. specializing in analytical models and database development, population dynamics, and modeling capabilities. Dr. David Rogowski is a Fish Biologist with the Arizona Game and Fish Department and is responsible for some of the long-term fish monitoring programs in Glen and Grand Canyons and is experienced in statistical models and database management. Laura Tennant and Clay Nelson are Fish Biologists at GCMRC with extensive field experience working with native and introduced fishes in the Colorado River. Dr. Molly Webb is a Research Fishery Biologist with the Bozeman Fish Technology Center, U.S. Fish and Wildlife Service specializing in the reproductive physiology and ecology of freshwater fishes. Dr. James Crossman is Fish Ecologist with BC Hydro in Vancouver, Canada and will be collaborating with Dr. Webb on the reproductive condition work proposed in H.2.

5.4. Consequences of Modified Proposals

The modification to the sampling design for Project H.2, entitled "Experimental Flow Assessment of Trout Recruitment", reduces the number of sub-reaches established in Glen Canyon from three to one. Each sub-reach is 3-km in length and in total represents about 36% of the sampleable area of the recreational fishery. The removal of the upper two sub-reaches (1A & 1B) reduces the number of independent replicates to test flow responses, and therefore, the strength of the inference is weakened for this LTEMP study. It is likely that we will be unable to develop a predictive model for estimating Age-0 recruitment due to reduced sampling. In general, observations from the past FY2018-20 TWP showed trends for higher rainbow trout recruitment of Age-0's and higher overall condition in the upper reaches compared to the lowest sub-reach 1C. However, retaining sub-reach 1C maintains continuity with past findings on RBT population dynamics (Natal Origin inception 2012), model development, and analyses. Secondly, the remaining data still provide us with a means to make comparisons between past and present estimates of abundance, and rates of growth, recruitment, and survival (i.e., the loss of the upper two sub-reaches represents only a few years' worth of data). Currently, sub-reach 1C has the highest densities of large sized brown trout; however, the upper two sub-reaches are showing increases in brown trout density and recruitment of juveniles. The system-wide reduction in the total number of brown trout that we are able to tag and later recaptured will likely reduce our ability to make precise population estimates for this troublesome species in outlying years. Lastly, we will less likely be unable to assess the efficacy of brown trout harvesting efforts by NPS.

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7. Budget

Fiscal Year 2021								
Project H Salmonid Research and Monitoring Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
H.1 Rainbow trout monitoring in Glen Canyon (AGFD)	$9,924	$0	$2,000	$14,111	$88,000	$0	$6,285	**$120,320**
H.2 Experimental flow assessment of trout recruitment (TRGD)	$83,130	$500	$42,816	$182,750	$37,000	$0	$44,397	**$390,594**
H.3 Brown Trout Early Life Stage Survey (BTELSS)	$33,285	$12,950	$100	$37,303	$0	$0	$11,709	**$95,347**
H.4 Salmonid modeling	$49,312	$0	$0	$0	$83,000	$0	$9,394	**$141,705**
Total Project H	**$175,651**	**$13,450**	**$44,916**	**$234,164**	**$208,000**	**$0**	**$71,785**	**$747,966**

Fiscal Year 2022								
Project H Salmonid Research and Monitoring Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
H.1 Rainbow trout monitoring in Glen Canyon (AGFD)	$10,123	$0	$1,300	$14,200	$88,000	$0	$8,277	**$121,900**
H.2 Experimental flow assessment of trout recruitment (TRGD)	$91,408	$5,000	$17,272	$84,805	$17,000	$0	$44,177	**$259,662**
H.3 Brown Trout Early Life Stage Survey (BTELSS)	$30,368	$0	$0	$0	$0	$0	$6,681	**$37,049**
H.4 Salmonid modeling	$39,762	$0	$0	$0	$43,000	$0	$10,038	**$92,799**
Total Project H	**$171,661**	**$5,000**	**$18,572**	**$99,005**	**$148,000**	**$0**	**$69,172**	**$511,410**

Fiscal Year 2023								
Project H Salmonid Research and Monitoring Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
H.1 Rainbow trout monitoring in Glen Canyon (AGFD)	$10,325	$0	$1,300	$14,291	$88,000	$0	$9,897	**$123,813**
H.2 Experimental flow assessment of trout recruitment (TRGD)	$78,698	$5,000	$14,272	$86,471	$17,000	$0	$52,154	**$253,595**
H.3 Brown Trout Early Life Stage Survey (BTELSS)	$0	$0	$0	$0	$0	$0	$0	**$0**
H.4 Salmonid modeling	$58,389	$0	$1,500	$0	$43,000	$0	$18,059	**$120,948**
Total Project H	**$147,413**	**$5,000**	**$17,072**	**$100,762**	**$148,000**	**$0**	**$80,109**	**$498,356**

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

1. Investigators

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

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 (U.S. Department of Interior, 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.

Long-term monitoring allows the ability to detect trends and test hypotheses in regard to temporal variation in fish populations, but its strength also lies in the ability to interpret and detect unexpected trends or surprises (Lindenmayer and others, 2010; Dodds and others, 2012; Melis and others, 2015). When designed properly, a long-term monitoring program is a powerful tool for quantifying the status and trends of key resources, understanding system dynamics in response to stressors, and investigating the efficacy of alternative management actions. Without long-term monitoring, science-based decisions for fisheries management are often not possible (Walters, 1986). This project will continue long-term, standardized monitoring conducted by AGFD 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. This is the only project that tracks all native and nonnative fishes throughout the length of the Colorado River in the project area.

AGFD will conduct one spring system-wide fish monitoring trip in FY2021, one trip in FY2022, and two trips in FY2023 from Lees Ferry to Diamond Creek using electrofishing, angling and hoop netting. For the monitoring that takes place in the Fall downstream from Diamond Creek, AGFD will only monitor the last 15 miles of river upstream from Pearce Ferry (3 nights of sampling in FY2021, FY2022, and FY2023) due to budget constraints and the need to reduce logistics costs. Other fish monitoring efforts which focus on humpback chub (Project G), and monitoring of small bodied fished conducted by the National Park Service (NPS) downstream of Bright Angel Creek (funded by the Bureau of Reclamation outside of the Glen Canyon Dam Adaptive Management Program; GCDAMP) also provide important additional detection information of new invasive aquatic species, and all of these efforts together provide a robust monitoring program to track changes in native fishes and detect new problematic invasive aquatic 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 fishes, it also increases the likelihood that warm-water introduced fishes will become established and negatively impact populations of native fishes. Management and removal of invasive aquatic species can be difficult once a species becomes established because problems typically become large in scale quickly and few effective tools are available for managing aquatic invasive species (Dawson and Kolar, 2013).

This creates the need to both detect invasive species early and understand which species pose the greatest threats so that efforts can be prioritized. Assessing the risks posed by existing or new warm-water invasive fish provides managers with the scientific information needed to make decisions about what management activities are warranted. Hilwig and Andersen (2011), compiled a literature review of the potential risks posed by individual species, but those risks need to be validated and quantified based on existing environmental conditions, species abundances, and expected future conditions in the Little Colorado River (LCR) and Colorado River ecosystem (CRe). In previous work plans risks related to rainbow and brown trout were evaluated (FY2016-17) as well risks posed by other invasive warm-water fishes (FY2018-20). Channel catfish and green sunfish were identified as two invasive species that pose particularly high risks to Colorado River native fish (Ward, 2020).

In surveys conducted in FY2018-20, channel catfish were found to exist in higher abundance within the LCR than previously known, with a majority of the fish being large in size, averaging 408 mm (Figure 1). There are no catfish species native to the Colorado River, therefore native Colorado River fishes did not evolve mechanisms to avoid catfish predation. Native fishes are particularly vulnerable to predation by catfish predators (Ward and Figiel, 2013), 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 (Ward, 2015). In this workplan we propose to focus specifically on quantifying the risks posed by these two species.

Laboratory studies will be conducted to quantify size specific predation risk from channel catfish and green sunfish. These laboratory studies in conjunction with abundance estimates for channel catfish from the LCR, will allow managers to determine if invasive catfish present more or less of a predation threat to juvenile chub than predation by trout or other warm-water predators. This information gives context from which to evaluate potential management actions such as mechanical removal and will ensure that any future aquatic invasive species removal efforts are focused only on those species that pose the highest threat to humpback chub populations.

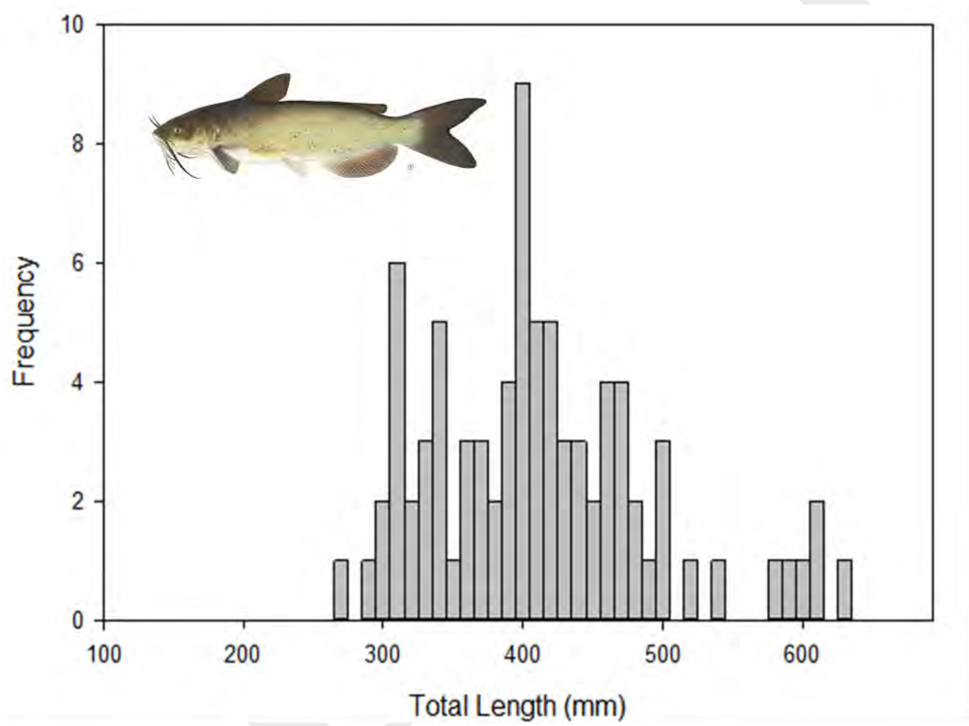

Figure 1. Size distribution of channel catfish caught in the Little Colorado River in 2019 from the confluence to Atomizer Falls (river km 13.5). Eighty-two fish were caught using angling in 109 hours of effort. Average total length was 408 mm which indicates channel catfish are relatively abundant and large, indicative of a high potential for negative impacts on humpback chub within the Little Colorado River.

In addition to evaluating the risks posed by invasive fishes we will also continue to evaluate the risks posed by infestation of Asian fish tapeworm (*Bothriocephalus acheilognathi*) in humpback chub. Asian fish tapeworm is an invasive species that infests warm-water cyprinid fish. Asian fish tapeworm monitoring took place in 2005 and 2006 and has occurred annually at a low level within the LCR since 2015.

Additional monitoring will continue in this work plan to evaluate the prevalence of Asian fish tapeworm in humpback chub inhabiting the mainstem Colorado River as identified in the 2016 BiOp. Asian fish tapeworm has been identified as one of six potential threats to the continued existence of endangered humpback chub (USFWS, 2002). It is potentially fatal to new host species (Hoffman and Schubert, 1984).

Asian fish tapeworm was first documented in the LCR in Grand Canyon in 1990 (Minckley, 1996) and was hypothesized to be a cause of long-term declines in condition of adult humpback chub from the LCR (Meretsky and others, 2000). Monitoring Asian fish tapeworm infestation in humpback chub in the mainstem Colorado River in addition to the LCR will provide a baseline context and relative risk assessment with which to evaluate the potential impacts of this invasive parasite on humpback chub populations.

In the FY2018-20 Triennial Work Plan (TWP) we identified the need to develop a new tool to detect rare nonnative species invasions prior to population expansion. Responding quickly to invasions before populations become large and established is the least expensive and most effective way to control invasive species (Leung and others, 2002). Early detection tools are in the process of being developed to detect the presence of rare species and their spatial extent across a riverscape at a molecular level (Schwartz and others, 2007; Carim and others, 2016a). In aquatic environments, fish shed cellular material into the water via reproduction and feces that can persist in the environment for several weeks. This cellular material can be collected via water sample and environmental DNA (eDNA) extracted from cells collected in the environment in which an organism lives, rather than directly from animals themselves.

Since the quantity of eDNA in a sample scales with fish biomass, relative abundance metrics can be calculated (Klymus and others, 2015). This approach can have higher sensitivity relative to traditional sampling methods, since hoop nets and standard electrofishing may not detect rare species at the early stages of invasion (e.g., smallmouth bass), species that may not be susceptible to capture (e.g., channel catfish), or species residing in deeper areas outside of the range of standard methods. Molecular analyses can also be associated with lower costs than traditional staff-heavy sampling methods, since a filtered water sample is all that is needed (Carim and others, 2016a). As such, this tool lends itself nicely to answering questions in the Grand Canyon related to both the presence and distribution of rare nonnative species and is a critical first step in early detection so that management actions can be targeted to prevent spread.

We used seed money in the FY2018-20 TWP in combination with funding from the USBR and US Fish and Wildlife Service (USFWS) to commence a project to collect eDNA samples at 300 spatially distributed sites throughout the Colorado River, at tributary junctions, and in Lakes Mead and Powell. This trip was scheduled to launch in May 2020 but was postponed due to the COVID-19 pandemic and closure of the Colorado River in Grand Canyon in spring 2020. This sampling may be postponed to June 2020 or rescheduled entirely to May 2021.

In the FY2021-23 TWP, we propose to use data on any nonnative species detections from the 2020 eDNA sampling trip to target reaches where problematic nonnative species detections occur. The objective of this second sampling trip is twofold: 1) determine whether invasive species of interest have geographically expanded; and 2) determine whether relative abundance has increased (or decreased) in the interim time period. This information will be used to help the NPS implement strategies that respond to new or expanded invasions, should they occur.

3. Hypotheses and Science Questions

- What is the species composition, relative abundance, longitudinal distribution and population trends of the fish assemblage inhabiting the CRe?
- What is the incidence of infestation of Asian fish tapeworm in humpback chub in the mainstem Colorado River and what risks does this parasite pose?
- What warm-water nonnative fishes are present in the CRe and how can we improve our ability to detect new invasions of warm-water nonnative fish before they become established? Can new eDNA tools be used to effectively collect this information?
- What are the current impacts of the existing population of introduced channel catfish on juvenile humpback chub in the LCR and are those impacts more or less of a threat than predation by other introduced fishes?

4. Background

Prior to construction of Glen Canyon Dam water temperature in the Colorado River in Grand Canyon historically fluctuated from near freezing in the winter to almost 30°C in the summer (Vernieu and others, 2005) and was highly turbid during most of the year (Voichick and Topping, 2014). During this period, the Colorado River was dominated by native fish and introduced warm-water fish such as channel catfish (Hayden, 1992; Minckley and Marsh, 2009). These warm-water fish can handle cold winter water temperatures but need warmer water to grow and complete their life cycle. With the completion of Glen Canyon Dam in 1963 and subsequent filling of Lake Powell, river temperatures dropped to 7-10°C by 1973 with little annual variation. This shift in the thermal regime dramatically altered the fish assemblage of the Colorado River in Grand Canyon, changing it from an assemblage dominated by warm-water species to one dominated by cold-adapted rainbow trout.

This condition persisted for approximately 22 years. Constant cold water has largely kept warm-water introduced fish from becoming established throughout Glen, Marble and most of Grand Canyon. Cold water releases from Lake Powell persisted from 1983, when the reservoir filled completely, until 2005 when drought conditions caused water elevations in Lake Powell to drop and warmer surface waters became entrained in the penstocks and released downstream (8-16°C), once again creating a varied thermal regime in the Colorado River in Glen, Marble and Grand canyons.

This recent period of warmer water caused by drought conditions, within a system dominated by cold water for a long time, may be one reason for the unique pattern of native fish increases in recent years in the CRe, compared to dramatic declines that have occurred in most other portions of the Colorado River Basin during the same time period.

In cooperation with AGFD, fish community monitoring occurs in the spring from Glen Canyon Dam to Pearce Ferry (RM 281) (476 kilometers) using a variety of methods: boat-mounted, DC electrofishing conducted at night, angling, and hoop nets. Methods were standardized in 2000 and employ a spatially stratified random sampling design to provide a catch-per-unit-effort index of abundance for the fish species that are present (Speas and others, 2004). This long-term, system wide monitoring program provides the baseline context under which population changes can be compared and assessed. We propose to continue this long-term system-wide monitoring because it provides important trend information on multiple species of native and nonnative fish throughout the CRe.

This monitoring program also provides detection capability for new warm-water invasive fish which may be entering the CRe from Lake Powell by passing through Glen Canyon Dam, descending tributaries such as the LCR, or swimming upstream from Lake Mead. To better assess native and nonnative fish trends downstream of Diamond Creek, AGFD will continue to conduct an annual fish monitoring trip in this section of the river. The elevation of Lake Mead has decreased due to drought and the Colorado River has reemerged in areas that were previously inundated. Sampling downstream of RM 225 began in 2007 and downstream of RM 270 in 2015.

This section of river is of particular interest because western Grand Canyon holds large numbers of native fish, relative to upstream segments. For this reason, AGFD has increased the spatial extent of its downstream monitoring effort in the reach immediately upstream of Pearce Ferry. Recent catches of humpback chub and other native species in hoop nets have been highest in the reaches from just upstream of Diamond Creek downstream to Pearce Ferry (RM 220 – 281). These results suggest a possible range expansion of humpback chub in western Grand Canyon (Van Haverbeke and others, 2017; Rogowski and others, 2018). Additionally, in 2012, AGFD captured the first razorback sucker observed in this system in over 20 years with subsequent detections in 2013, 2016 and 2018. The reach downstream from Pearce Ferry to Lake Mead (RM 281 – 296) may also be important habitat for native fish, including the endangered humpback chub and razorback sucker; however, this area is not monitored by this program as it lies outside of Grand Canyon National Park, thus outside the purview of the GCDAMP.

Nonnative fishes typically have detrimental impacts on the stability of native fish communities (Eros and others, 2020), and these effects can be exacerbated by drought conditions (Rogosch and others, 2019. Identifying sources of warm-water invasive fish in the CRe early improves the likelihood that a successful rapid containment/eradication response can be accomplished before negative impacts on endangered populations occur (Martinez and others, 2014). Preventing the introduction and spread of warm-water invasive fish is far more environmentally and fiscally desirable than undertaking control or eradication efforts after they become established (Martinez and others, 2014; Cucherousset and Olden, 2011).

Invasive fish have high proliferative potential, and once established, eradication is often essentially impossible and control typically requires long-term and expensive efforts (Martinez and others, 2014; Pimentel and others, 2000; Simberloff, 2003; Mueller, 2005; Johnson and others, 2009; McIntosh and others, 2010).

As indicated in the 2016 BiOp for the LTEMP EIS, the Bureau of Reclamation will conduct planning and compliance for implementation of rapid response control efforts for newly establishing or existing deleterious invasive species within and contiguous to the action area (USFWS, 2016). Before any management actions can occur, monitoring must first detect those invasions and research must be conducted to evaluate risks and inform managers whether control efforts are actually warranted and feasible. This project provides the information that will allow for effective integration of monitoring, research, and invasive species management.

5. Proposed Work

Project Elements

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

David Rogowski, Fish Biologist, AGFD
Jan Boyer, Fish Biologist, AGFD
Cory Neilson, Fish Biologist, AGFD
David Ward, Fish Biologist, USGS, GCMRC

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, AGFD has conducted two spring river trips from Lees Ferry to Diamond Creek, and one fall river trip from Diamond Creek to Pearce Ferry (4 nights), 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 CRe.

The current work plan will continue this standardized monitoring (14 nights of sampling per spring trip) which has been occurring annually since 2000 (Makinster and others, 2010) with the change that only as single spring downstream monitoring trip will occur in FY21 and FY22.

For the monitoring that takes place in the Fall downstream of Diamond Creek, in FY 22 and FY 23 only the last 15 miles of river above Pierce Ferry will be monitored (3 nights of sampling each year), because of budget constraints and the need to reduce logistics costs.

For sampling purposes, the Colorado River is divided into 83 reaches 5 miles (8 km) in length. Reaches are shorter where rapids define the upstream and downstream extent of a reach. Sample sites within a reach are 250 m in length on both sides of the river. Sampling reaches will be selected using a spatially stratified random approach (Grafström and Tillé, 2013; Robertson and others, 2013) equivalent to the number of nights sampling in a trip, with the probability of selection weighted according to the percent of available sample sites within that reach relative to the total sampling area (spring: RM 0 - 281.4, n = 3,507 available sites, autumn: RM 226 - 281.4, n = 741 available sites). After a reach is selected, sample sites (24 electrofishing, 16 hoop net) are randomly selected for each reach (40 sites = approximately 65% of sites available in a 5-mile reach). In shorter reaches, sample size is reduced so that 66% of available sites are selected.

Electrofishing will occur at night (commencing with the appearance of two stars or planets) with two 16-ft Osprey sport boats outfitted with a boat electrofishing system, using an ETS (Electrofishing Systems, LLC) Complex Pulse System (CPS) unit (MBS-1DPQ-CR-AZ) powered by a 6,500W generator (Honda EG6500). The CPS units applied between 195 to 400 volts and 12.0 to 18.5 amperes to one spherical steel anode (25.4 cm diameter) partially submerged (~5 cm exposed) off the front of the boat. The aluminum boat hull acts as the cathode. As we move downstream, voltage is decreased, and amperage increased to maintain similar power output with increasing water conductivity. Seconds spent electrofishing a site are recorded as the unit of effort. Each electrofishing sample consists of a single electrofishing pass along a 250 m shoreline transect. Each boat is crewed by one boatman and one netter.

Hoop nets will be set overnight and measure 1.3 m long and 0.6 m in diameter with 6.35-mm mesh and consisted of three hoops and a single 0.1-m throat. All nets will be baited with approximately 117 g of Purina Aquamax fish food. Net set locations within the sample site are based on the ability to effectively secure the net depending on water depth, tie off structures, and river currents. Each night we will angle for channel catfish using spinning rods baited with Hillshire Farm Lil' Smokies sausages. Angling usually occurs in eddies at camp just before dark, for a minimum of one hour of angling effort per site.

Parasite monitoring

In addition to evaluating the risks posed by invasive fish this project element will also continue to evaluate prevalence of fish parasites such as Lernea and Asian fish tapeworm in humpback chub. Lernea are documented on fish using visual inspection during routine monitoring, and Asian tapeworm will be assessed from a small sample of fish using non-lethal methods (Ward, 2007). Monitoring of fish parasites such as Lernea and Asian fish tapeworm is identified as a requirement of the 2016 BiOp for operation of GCD. To monitor for Asian tapeworm, 30 to 60 humpback chub of various sizes will be held on the riverbank in an 1893-l collapsible tank and will be treated according to methods described in Ward, 2007, where individual fish are held in perforated buckets inside a larger holding tank treated with Praziquantel at 6 mg/l. Each fish will receive a Praziquantel treatment and be held for 48 hours with the number of tapeworms quantified from each individual fish. Praziquantel has been used since 1985 to remove parasites in many different fish species in hatcheries. Following treatment all fish will be released alive back into the river. These methods are identical to those that have been used in ongoing Asian tapeworm monitoring within the LCR. Monitoring for Asian fish tapeworm infestation in humpback chub will occur within the mainstem Colorado River to include one area in eastern Grand Canyon and one sample in Western Grand Canyon on alternating years as well as within the Little Colorado River annually. This monitoring effort will be used to establish an annual baseline infection level by fish size and used to evaluate the potential impacts of Asian fish tapeworm on humpback chub populations inhabiting the mainstem Colorado River. This information will be used to determine whether year-to-year variation in the prevalence of tapeworm infestation is linked to annual variation in growth, survival, or abundance of juvenile humpback chub in the mainstem Colorado River. These samples, although very limited because of budget constraints, will provide a minimum baseline context with which to evaluate potential changes in parasite abundance and impacts of this invasive parasite on endangered humpback chub populations.

Fish mortality

As part of this work element GCMRC will also summarize and report on the number of native and nonnative fish that were caught as well as euthanized throughout the CRe annually from all fish monitoring projects. This summary information will quantify the taking of life that occurs within the canyon in response to Tribal concerns and will also facilitate identification of range expansions or new aquatic invasive species detections that might not be apparent without evaluations across projects conducted by various cooperating agencies.

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

David Ward, Fish Biologist, USGS, GCMRC
Kim Dibble, Fish Biologist, USGS, GCMRC
Eric Frye, Research Assistant, USGS, GCMRC
David Rogowski, Fish Biologist, AGFD
Kenneth Hyde, Chief of Science and Resource Management, Glen Canyon NRA

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 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 passing through the dam and attempting to colonize the -12 mile slough.

In addition, AGFD will continue to conduct an additional night of monitoring during their Lees Ferry long-term trout monitoring in summer and autumn. These additional electrofishing sites increase potential detection of new invasive fish passing through the dam. This monitoring is focused in areas known to harbor invasive fishes, such as the area directly below the dam (walleye, *Sander vitreus*), the slough at -12 mile, and other areas with warm shallow water or spring inputs. Tributaries are another high-risk pathway for warm-water fish invasions. This project also proposes to assess the relative abundance of introduced fish that are typically washed into the Colorado River during the monsoon season from isolated pools where they reproduce within the LCR, Kanab Creek, and Spencer Creek drainages and to evaluate the potential threat that invasions and colonization events of fish emanating from these tributaries pose for Colorado River native fish.

Because of budget and personnel constraints, only a single tributary will be surveyed in this work plan. We will focus on the area between Grand Falls and Blue Springs within the LCR drainage. The survey will consist of hiking and counting the number of pools present prior to the monsoon season that are likely to provide environments for warm-water invasive fish to thrive and providing photo documentation of those environments. In addition, seining or electrofishing a subsample of those pools will provide a relative abundance estimate of invasive fishes that are present. This survey conducted on Navajo Nation lands will be coordinated with Tribal partners.

eDNA sampling

Traditional field methods including hoop netting and standard electrofishing may not detect rare species at the early stages of invasion, species with low susceptibility to capture, or species residing in deeper areas outside of the range of standard sampling methods. The nonnative species currently present in the Colorado River are only a fraction of the potential invasive fish species that could establish, especially if water temperatures increase as Lake Powell elevations decline in the future (Dibble and others, *in prep*). Many warmwater nonnative species that are not yet established in Grand Canyon have caused population declines and extirpations in other southwestern river systems (Johnson and others, 2008; Martinez and others, 2014).

As such, knowledge about the current distribution and abundance of rare nonnative fishes relative to recovering populations of humpback chub and razorback sucker is a necessary first step in understanding risk and implementing strategies to address expansion of existing populations or invasion of new aquatic species as the ecosystem changes.

Using information on the spatial distribution and relative abundance of rare nonnative species in Grand Canyon gained from our May 2021 eDNA sampling trip, combined with targeted studies in 2020-2021 to refine sampling methodology related to turbidity in Grand Canyon, we propose to resample a subset of sites approximately two years later to: 1) determine whether problematic nonnative species are detected in the same geographic area or if expansion (or contraction) is occurring, and 2) determine whether nonnative species relative abundance is increasing (or decreasing) based on the amount of DNA in the water column. This shortened follow-up trip will occur in early summer, a period when nonnative fish activity is high during growing season and turbidity is low prior to the onset of monsoon season, allowing for faster sample filtration. Environments near the bank will be sampled as they are associated with higher fish density.

These data will be compared to fish data collected via electrofishing and hoop netting during the spring 2022 systemwide sampling trip conducted by AGFD (Project Element I.1). AGFD sampling reaches are randomly assigned throughout the canyon, so we will compare our results to known detections/non-detections of nonnatives in areas of overlap between our sampling designs. In addition, we will collect two samples (one per riverbank) per site and randomly select one bank to analyze. If an eDNA detection occurs on one bank, we will analyze the second bank to estimate detection probability for target species of interest. We will also take three samples at camp every night, three samples above each tributary, and three samples in each tributary in the same location to assess detection probability.

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

David Ward, Fish Biologist, USGS, GCMRC
Laura Tennant, Fish Biologist, USGS, GCMRC
Clay Nelson, Fish Biologist, USGS, GCMRC
Eric Frye, Research Assistant, USGS, GCMRC

The objective of this project element is to quantify the potential impacts channel catfish may have on native fish populations in the LCR. Work conducted in the FY2018-20 TWP indicates large channel catfish are present in higher abundance in the LCR than previously known and distributed from the confluence to Atomizer Falls encompassing the entire area inhabited by humpback chub within the LCR. In this work plan, we will continue to catch and mark (Passive Integrated Transponder tag) channel catfish in the LCR using angling techniques to obtain estimates of population size, distribution and size structure. Channel catfish can have negative impacts on native fish populations through both competition and predation. In this work plan we will focus on quantifying the potential negative impacts related to predation. Field evaluations of channel catfish diets will be used in conjunction with relative abundance data to predict population level predation impacts of these warm-water invasive fish on humpback chub within the LCR. New gastric lavage techniques recently shown to be effective on the San Juan River (Heddon and others, 2020) will be evaluated in the laboratory and utilized and, if effective, to collect diet data for channel catfish within the LCR. Because the LCR is an area of particular sacred importance to several Tribes, all efforts will be made to avoid taking of life in this sensitive area. If non-lethal gastric lavage techniques cannot be utilized, stable isotope analysis using non-lethal tissues samples will also be explored if budgets permit. Stable isotope analysis has advantages over traditional stomach content analysis and can also yield information on competitive effects of invasive species (Ruiz and others 2020). Efforts will be made to ensure that any sample of catfish euthanized for diet or age analysis are also utilized for beneficial use in consultation with the Tribes.

Relative size specific predation vulnerability of humpback chub to channel catfish will also be assessed in the laboratory in overnight trials using methods similar to those employed for rainbow and brown trout and smallmouth bass in previous work plans (Ward and Morton-Starner, 2015; Ward and others, 2016; Tennant, 2018; Ward and Vaage, 2019). Twelve replicate tanks at 20°C will be used to evaluate relative predation vulnerability among species for multiple size classes of juvenile humpback chub to channel catfish in overnight under varying environmental conditions. Field evaluations of catfish diets and abundance data from the LCR in combination with laboratory predation information under varying environmental conditions will be used to model population-level impacts of channel catfish on humpback chub at various life stages.

Predation on humpback chub by channel catfish has the potential to be high but impacts have not been quantified. Competitive effects may also be present, but in this work plan we will focus only on quantifying predation impacts. Management actions to control these species may be warranted depending on the magnitude of predation and competition interactions. Control of channel catfish within the LCR may be more cost effective than trout removal in the mainstem Colorado River if they are having population-level impacts on humpback chub. These data will allow managers to improve decisions about management actions designed to conserve Colorado River native fish and ensure that any future management actions that are undertaken are focused only on only those fish that are having the most detrimental impacts on native species.

5.2. Outcomes and Products

Project Element I.1.

Outcomes:

- Monitoring and detection of trends in distribution and relative abundance of native and nonnative fish in the Colorado River. Evaluations of fish condition, growth, and movement relative to environmental conditions.

Products:

- AGFD trip reports and Annual Report, AGFD Oral Annual presentations at the Grand Canyon Fish Cooperators Meeting and the GCDAMP Annual Reporting Meeting, AGFD Conference Presentations at the annual Desert Fishes Council Meeting, AGFD Conference presentation(s) at the joint annual meeting of the American Fisheries Society and Wildlife Society AZ/NM chapter meetings and Colorado River Aquatic Biologists Annual Meeting, USGS Journal article summarizing Asian Tapeworm monitoring trends, 1-2 peer reviewed journal articles by AGFD during this work plan on issues related to Colorado River fishes.

Project Element I.2.

Outcomes:

- Risk assessment for pathways of warm-water fish invasion and colonization into the Colorado River in Glen and Grand Canyon. Early detection of invasive aquatic species.

- Products: USGS trip reports provided to Tribes related to risk of invasive fish descending tributaries during monsoon flood events, USGS oral presentation on effectiveness of eDNA sampling for detection of invasive fishes in Grand Canyon at GCDAMP Annual Reporting Meeting, USGS oral presentation on invasion and colonization dynamics of green sunfish below Glen Canyon Dam at GCDAMP Annual Reporting Meeting.

Project Element I.3.

Outcomes:

- Model population-level impacts of channel catfish on humpback chub at various life stages and an evaluation of the relative risk that channel catfish pose to humpback chub vs. other nonnative fish predators.

Products:

- USGS journal article on impacts of channel catfish on humpback chub populations within the LCR, USGS oral presentation on impacts of channel catfish on humpback chub in the LCR given at the GCDAMP Annual Reporting meeting and at the Annual Desert Fishes Council Meeting.

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7. Budget

Fiscal Year 2021								
Project I Warm-water Native and Non-Native Fish Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							14.00%	
I.1. System-wide native fish & invasive aquatic species monitoring (AGFD)	$12,640	$0	$11,920	$46,571	$217,550	$0	$16,485	**$305,166**
I.2. Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$70,601	$1,500	$3,000	$7,029	$21,000	$0	$12,128	**$115,258**
I.3. Impacts of channel catfish in the LCR	$104,693	$1,500	$6,600	$3,100	$0	$0	$16,225	**$132,118**
Total Project I	**$187,934**	**$3,000**	**$21,520**	**$56,700**	**$238,550**	**$0**	**$44,838**	**$552,542**

Fiscal Year 2022								
Project I Warm-water Native and Non-Native Fish Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							22.00%	
I.1. System-wide native fish & invasive aquatic species monitoring (AGFD)	$10,123	$0	$10,000	$47,279	$217,550	$0	$21,355	**$306,307**
I.2. Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$86,590	$0	$500	$23,356	$55,560	$0	$25,965	**$191,970**
I.3. Impacts of channel catfish in the LCR	$137,078	$0	$1,600	$3,200	$0	$0	$31,213	**$173,091**
Total Project I	**$233,790**	**$0**	**$12,100**	**$73,835**	**$273,110**	**$0**	**$78,533**	**$671,368**

Fiscal Year 2023								
Project I Warm-water Native and Non-Native Fish Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
I.1. System-wide native fish & invasive aquatic species monitoring (AGFD)	$10,325	$0	$6,000	$87,481	$217,550	$0	$35,592	**$356,948**
I.2. Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$108,972	$0	$0	$7,047	$21,000	$0	$33,115	**$170,134**
I.3. Impacts of channel catfish in the LCR	$101,277	$0	$1,100	$0	$0	$0	$28,666	**$131,043**
Total Project I	**$220,574**	**$0**	**$7,100**	**$94,528**	**$238,550**	**$0**	**$97,373**	**$658,125**

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

Budget constraints and the need to reduce costs have resulted in reduction of effort for the system-wide electrofishing that is conducted annually by AGFD. Project I.1 was reduced such that only a single sampling trip will occur in FY2022 and FY2023. Monitoring downstream of Diamond Creek was also reduced by one night of sampling in FY2022 and FY2023. Budget constraints will also result in laying off one USGS GS-9 Fish Biologist in FY23 (Clay Nelson). This loss of a qualified field biologist limits the amount of field and lab work that can be conducted in FY2023 and negatively impacts projects G, H and I.

Project J: Socioeconomic Research

1. Investigators

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

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 USGS Grand Canyon Monitoring and Research Center (GCMRC). The project elements improve the ability of 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 FY2018-20 Triennial Work Plan (TWP) (Bureau of Reclamation, and U.S. Geological Survey, 2017):

- 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 Environmental Impact Statement (LTEMP EIS; U.S. Department of Interior, 2016a) (Element 1);
- The design, implementation, and monitoring of the impacts of an incentivized harvest program to reduce brown trout abundance in Lees Ferry (Element 2); and
- The survey of recreational angler and whitewater boater's preferences for flow attributes, 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, 2016b) resource goals related to humpback chub, sediment, invasive fish, and hydropower, as specified in Section 4.

Project Element J.1. Predictive Models for Adaptive Management

This project element will build on the dynamic programming methods developed to integrate rainbow trout and humpback chub population models and cost-effectiveness analysis, used to identify efficient management actions to meet adult humpback chub abundance goals (Bair and others, 2018; Donovan and others, 2019). Current research includes the exploration of which uncertainties in humpback chub population parameters have the greatest implications for management decisions (i.e., quantitative adaptive management model) and the explicit trade-offs (efficacy and cost) between Trout Management Flows (TMFs) and rainbow trout removals at the Little Colorado River. This element will further explore which drivers, linkages and uncertainties associated with experimental flows have the greatest implications for sediment resource management decisions and address the impacts of monitoring and research priorities on optimal biological management policies. These advancements require the integration of hydropower objectives into the modeling of sediment resources and will be a primary focus of Element 1, building on recent advancements in methods for predicting sandbar volume (Mueller and others, 2018; Mueller and Grams, 2018). Integration of hydropower objectives is an incremental step in the development of predicative models for adaptive management within the GCDAMP. The addition of hydropower objectives is timely given experimental flows proposed in the LTEMP EIS (see Project N).

Element 1's focus on adaptive management modeling is consistent with the GCDAMP fisheries review panel's recommendation that the program, "adopt [a] decision theoretic approach to adaptively manage the rainbow trout fishery and humpback chub population" (Casper and others, 2016). A decision-theoretic approach to adaptive management is when a "predictive model or set of models are created that represent alternative ideas of how the system works" and those priors are evaluated through predicted or actual future resource states (Casper and others, 2016). This approach would allow the GCDAMP to "optimize" monitoring and research by identifying the relative efficiency of learning opportunities.

Project Element J.2. Brown Trout Incentivized Harvest

This project element will support the National Park Service Glen Canyon National Recreation Area (GCNRA) in the design, implementation, and monitoring of the impacts of an incentivized harvest program to reduce brown trout abundance in Lees Ferry. The dearth of research on aquatic incentivized harvest programs means that how and to what degree Lees Ferry anglers respond to harvest incentives is uncertain (Best, 2006).

Program participation will hinge on monetary incentives, social norms, and the amount and type of information anglers have regarding fish abundance and harvest incentives. Element 2's objective is to reduce uncertainty surrounding program design by monitoring and researching harvest incentive outcomes under a range of assumptions regarding anglers' willingness to participate and sensitivity to incentive pricing.

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 the importance of seasonal and flow attributes to recreational users in Glen and Grand Canyons (Bair and others, 2016; Duffield and others, 2016; Neher and others, 2018).

This research 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). However, 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 preferences associated with specific daily flow stage and fluctuation remain. For example, Neher and others (2018) did not find a difference between whitewater boater's preferences regarding daily fluctuations of 8,000 ft^3/s and constant flows. However, Bishop and others (1987) found a strong difference between whitewater boater's preferences for large fluctuations (10,000 – 31,500 ft^3/s) and constant flows at moderate levels (22,000 ft^3/s). In addition, 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 daily fluctuations, warrant further study of recreational preferences for flow attributes.

3. Hypotheses and Science Questions

Hypotheses in Project Element J.1. Predictive Models for Adaptive Management:

- Monitoring strategies for biological resources (e.g., invasive and native fish) lead to variation in observational uncertainty, which has a direct impact on the effectiveness and efficiency of optimal biological resource management strategies.

- Flow actions that improve and support the long-term stability of downstream resources (e.g., sediment) are also able to maintain or improve the value of hydropower generation at GCD.

Hypotheses in Project Element J.2. Brown Trout Incentivized Harvest:

- Monetary harvest incentives will have a direct impact on the number of angler trips, targeting behavior, and retention rates of brown trout at Lees Ferry.

Hypotheses in Project Element J.3. Recreation Monitoring and Research:

- Specific hypotheses to be addressed will be determined in coordination with the Socioeconomics Ad Hoc Group (SEAHG) during Element 3 implementation and development.

4. Background

Project J will meet critical socioeconomic information needs identified by the GCDAMP (AMWG, 2012a). Furthermore, the implementation of proposed management actions in the Expanded Non-Native Aquatic Species Management Plan in the Glen Canyon National Recreation Area (GCNRA) and Grand Canyon National Park (GCNP) below Glen Canyon Dam (U.S. Department of Interior, 2019) and experiments in the LTEMP EIS are, “contingent on the responses of one or more socioeconomic metrics” and the role of the GCMRC, and cooperators, is to provide information on biological and physical resources while also providing information related to socioeconomic aspects of resources (VanderKooi and others, 2017).

Element 1 will focus on development of predicative models for adaptive management, utilizing research at GCMRC, to formally model resource tradeoffs and prioritize monitoring and research. This is important because it is the “absence of decision-making mechanisms” in adaptive management programs that make systematic prioritization of investment in monitoring, research, and management alternatives difficult (Scarlet, 2013). Including economic assessment of investment in monitoring and research is an important component of such programs (Doremus, 2010). While previous research has developed a decision support system for the Colorado River Ecosystem in GCNRA and GCNP downstream from GCD, modeling of management scenarios of other resources (e.g., sediment storage, native fish) were very uncertain due to limited empirical data (Walters and others, 2000). Utilizing ongoing biological and physical research by GCMRC and cooperators, Element 1 will continue to improve the GCDAMP’s ability to prioritize research, including evaluating proposed experiments and actions identified in the LTEMP ROD (U.S. Department of Interior, 2016b).

Element 1 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' (U.S. Department of Interior, 2016b). In accordance with the LTEMP ROD sediment and hydropower and energy resource goals, Element 1 will also 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 multiple years (U.S. Department of Interior, 2016b).

Element 2 and 3 address the LTEMP ROD nonnative invasive species and recreational experience resource goals. Element 2 initiates socioeconomic monitoring and research to facilitate the implementation of GCNRA's incentivized harvest program. The objective of the program is to control brown trout abundance through angler removal, consistent with the LTEMP ROD nonnative invasive species resource goal to, 'minimize or reduce the presence and expansion of aquatic nonnative invasive species' (U.S. Department of Interior, 2016b). Element 3, through identification of recreational preferences for specific flow attributes, allows the GCDAMP to better understand how to 'maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem' (U.S. Department of Interior, 2016b).

A research element that is not included in this project is regional economic impact analyses. Regional economic impact analysis would inform the program and assist in the socio-economic assessment of experimental operations at GCD. The Long-Term Experimental and Management Plan Environment Impact Statement undertook regional economic impact analysis and found no significant impact in regard to operation of GCD, including proposed experiments, over the next 20 years (U.S. Department of Interior, 2016b). However, as social conditions change, revisiting the regional economic impact of changes in operation at Glen Canyon Dam in future workplans may be warranted.

5. Proposed Work

Project Element J.1. Predictive Models for Adaptive Management

Lucas Bair, Economist, U.S. Geological Survey
Erich Mueller, Professor, Southern Utah University, Physical Science
Michael Springborn, Professor, UC Davis, Environmental Science and Policy
Charles Yackulic, Research Statistician, U.S. Geological Survey
Paul Grams, Research Hydrologist, U.S. Geological Survey

The objective of this project element is the continued development of predictive biological and physical 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 ROD (U.S. Department of Interior, 2016b). This project will further refine bioeconomic modeling methods to evaluate rainbow trout monitoring, research and management strategies in relation to humpback chub population goals (Bair and others, 2018; Donovan and others, 2019; ongoing research in FY2018-20 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, 2018).

Model development will focus on decision frameworks and analytical tools that best apply to the GCDAMP resources when considering the need for collaboration, complex biophysical and socioeconomic interactions, and stakeholder perspectives. This project element will be coordinated with monitoring and research of humpback chub (Project G), salmonids (Project H), and sediment (Project B) resources.

Sub-element: 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 (Donovan and others, 2019). In the FY2018-20 TWP, we continue to develop GCMRC’s bioeconomic modeling capacity to estimate the effectiveness and efficiency of 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; FY2018-20 TWP Project J.2) needed to inform on rainbow trout and humpback chub population dynamics. Specifically, we will assess the importance of precise estimates of adult humpback chub and rainbow trout recruitment and abundance in Lees Ferry and Marble Canyon, respectively, in the optimal control strategies of rainbow trout.

The Nonnative Fish Control Downstream from GCD Environmental Assessment (Reclamation, 2011), informally hypothesizes that mitigation of the effects of rainbow trout on humpback chub through flow actions may be more cost-effective in the long-run relative to the proposed nonnative removal efforts in the LCR reaches (Bureau of Reclamation, 2011). This is the type of hypothesis that is addressed in current research (Bureau of Reclamation and U.S. Geological Survey, 2017). This sub-element will address how monitoring strategies of rainbow trout and humpback chub abundance can be used to further refine and test this and similar hypotheses using the dynamic modeling methods develop to date (Donovan and others, 2019).

Sub-element: 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 FY2015-17 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, 2018).

The primary objective of this 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, dynamic modeling 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. Ultimately, 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. This project sub-element will allow us to test the hypothesis that flow actions that improve and support the long-term stability of downstream resources (e.g., sediment) are also able to maintain or improve the value of hydropower generation at GCD.

Analytical model development of downstream resources in support of adaptive management has been prioritized in past work plans, based on resources that exhibit significant economic value and/or that garner a significant portion of the GCMRC annual budget, are impacted by operational decisions at GCD, and have sufficient predictive modeling frameworks developed to assess future resource states (Bureau of Reclamation and U.S. Geological Survey, 2014). As with previous modeling efforts (Bair and others, 2018; Donovan and others, 2019) the proposed model development utilizes cost-effectiveness analysis.

Like cost-benefit analysis, cost-effectiveness analysis is a standard economic practice. However, cost-effectiveness fundamentally asks a different question than cost-benefit analysis. Cost-benefit analysis assigns an overall net benefit (or net cost) to a future management action. Cost-effectiveness analysis in-turn identifies the least cost alternative, when faced with competing or complimentary management actions, to reach a defined objective.

In this case, the objective is humpback cub recovery, as defined by the USFWS (U.S. Fish and Wildlife Service, 2002), or sediment retention in Grand Canyon as defined in the LTEMP ROD (U.S. Department of Interior, 2016b). Implementing cost-effectiveness analysis is consistent with the ROD's goal, not to maximize benefits but to determine an operation at GCD that limits impact to hydropower while meeting recovery and long-term sustainability of downstream resources (U.S. Department of Interior, 1996). There are several qualities of cost-effectiveness analysis that lends itself to the GCDAMP's task of evaluating and prioritizing management actions, monitoring and research where incremental decisions must be made, under uncertainty, understanding that many overarching objectives are set through public processes.

Incorporating biological, physical, and economic dynamics into predictive models for adaptive management are important steps in the development of an adaptive management framework. The models in Element 1 will be developed in cooperation with stakeholders, according to needs in evaluating LTEMP EIS experiments and the advancement of scientific knowledge at GCMRC. This deliberate process of building a decision support framework through the development of individual analytical, predictive models will enable analysts to identify monitoring and scientific information needs and screen policy options as the GCDAMP advances its goals. Results of Element 1 are essential in enabling the GCDAMP to better organize and evaluate the scientific monitoring and research results provided by GCMRC.

This project element is not fully funded. Funding for cooperators have been eliminated from the humpback chub sub-element and reduced from two years to one year of summer salary in the sandbars sub-element. This will limit advancement of this project.

Project Element J.2. Brown Trout Incentivized Harvest

Lucas Bair, Economist, U.S. Geological Survey
Josh Abbott, Professor, Arizona State University, School of Sustainability

The primary objective of this project element is to evaluate how structure of monetary payout from the GCNRA's incentivized harvest program influences participation, harvest, and retention rates within the brown trout fishery at Lees Ferry. Understanding these program outcomes and underlying behavioral factors will inform GCNRA on approaches to meet removal objectives for brown trout. There are several objectives that the brown trout incentivized harvest program should aim to meet through its design.

First and foremost, the program needs to be effective and accomplish the stated goal of removing brown trout from Lees Ferry over the course of the pilot program. The program design should also be cost-effective, allow for flexibility and timely adjustments in response to angler participation, and generate useful data for learning about the nuances of incentivized harvest program design and participation within Lees Ferry and in other contexts.

We plan to collect data on program participation throughout the pilot program, as well as during subsequent years of this incentivized harvest program. This data collection will generate information about who is participating in the program, and how the average participant might vary seasonally or as harvest incentives shift, and in what ways this program might be altered in order to best target the most susceptible margins of participation for different Lees Ferry anglers. 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 of field data, Project J.2 will undertake a survey of anglers following implementation of the program. The angler survey, utilizing similar angler survey methods in the FY2015-17 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 (Bureau of Reclamation and U.S. Geological Survey, 2014). In these surveys, we will elicit further socio-demographic information to expand upon the participation trends gathered from the field data. We will also ask those surveyed about current and alternate program design elements to augment our data on the impact of variable prices on program participation. Statistical models appropriate for the experimental design and elicitation format of the surveys will be developed to evaluate the relationship between price incentives impacting trip-taking, catch rate, and retention rate behavior of different classes of angler. This data will enable the most specific recommendations about information and education targeting, as well as optimal incentive pricing for targeting different angler classes. 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 incentivized harvest program and 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 and will allow us to test the hypothesis that monetary harvest incentives will have a direct impact on angler trips, targeting behavior, and retention rates.

Project Element J.3. Recreation Monitoring and Research

Lucas Bair, Economist, U.S. Geological Survey
Chris Neher, Economist, Montana State University, Department of Mathematical Sciences

The objective of this project element is to further refine our understanding of recreational preferences for specific flow attributes as controlled by operations at GCD and within the flow parameters of the LTEMP ROD (U.S. Department of Interior, 2016b). To accomplish the project element objective, recreational surveys will be conducted in accordance with maintenance and experimental flows (e.g., TMFs, extended duration HFEs) to better understand recreationists' preferences and economic values associated with flow attributes. Specifically, surveys of anglers in GCNRA and whitewater boaters in GCNP will be conducted immediately following a recreationist's experience with a maintenance or experimental flow. Prior to implementation of individual surveys, the SEAHG will convene to review hypotheses proposed by investigators.

A series of economic surveys will be conducted to obtain information on recreationists' preferences and economic values associated with flow attributes. Consistent with past research of angler and whitewater boater's flow preferences, the surveys will be designed to elicit economic values using contingent valuation or choice experiment instruments in addition to investigation into other quantitative and qualitative metrics of recreationists' preferences and perspectives. These metrics will provide useful when analyzing recreational impacts and operational decisions at GCD. Specifically, surveys of anglers in GCNRA and whitewater floaters in GCNP will include questions addressing flow characteristics unique to the experimental flow being evaluated, but applicable to overall operation of GCD and within the parameters of the LTEMP ROD. Participants will be intercepted during or immediately following a maintenance or experimental flow event, differing from past recreational surveys (Bishop and others, 1987; Neher and others, 2017), and respondents will either be interviewed on-site or sent a mail survey packet, with a follow-up protocol for non-responders.

The limited temporal nature of a maintenance or flow event requires that we attempt to intercept the entire population of recreational anglers or whitewater boaters that experience the flow event, either with on-site sampling methods or assistance from the AZDGF and GCNP. GCNP maintains a comprehensive mailing list of all members of private whitewater floater parties. No a priori attempt will be made to stratify the sampling based on guided or non-guided status (for both anglers and whitewater boaters). However, preferences and economic values of guided and non-guided anglers and whitewater boaters will be compared within the data analysis.

Statistical models will be developed to evaluate the relationship between preferences, economic value and experimental flow attributes. The models will provide information on the relative preferences and economic value for flow attributes and the marginal rates of substitution between flow and other trip attributes.

This information is necessary for the GCDAMP to make informed decisions about the economic tradeoffs that occur, with regard to recreation, when evaluating future management actions (see FY2015–17 TWP, Project Element 13.3).

5.2. Outcomes and Products

Products from this project, led by Lucas Bair, will include annual reports to the GCDAMP, presentations at TWG and AMWG meetings when appropriate, presentations at scientific meetings, and peer-reviewed scientific journal articles.

Project Element J.1. Predictive Models for Adaptive Management

- In FY2021-23, one manuscript will be prepared from the results of Project Element 1 for submission to peer-reviewed scientific journals. Conference presentations will occur in parallel with the development of the peer-reviewed scientific journals.

Project Element J.2. Brown Trout Incentivized Harvest

- In FY2021-23, one manuscript will be prepared from the results of Project Element 2 for submission to peer-reviewed scientific journals. Conference presentations will occur in parallel with the development of the peer-reviewed scientific journal.

Project Element J.3. Recreation Monitoring and Research

- Products from Element 3 will be determined in coordination with the SEAHG during implementation and development. When applicable, presentations will be given at TWG and AMWG meetings and at scientific meetings, and peer-reviewed scientific journal articles will be prepared.

5.3. Personnel and Collaborations

Project Element J.1. Predictive Models for Adaptive Management

Charles Yackulic and Paul Grams, co-principal investigators on Project Element J.1, are involved in fisheries (Project G, Project H) and sediment (Project B) monitoring and research projects, respectively, in this work plan. The Project J sandbars sub-element is not contingent on implementation of Project B element 5.

Project Element J.2. Brown Trout Incentivized Harvest

Research objectives for Project Element J.2. will be achieved through collaboration between GCNRA, GCMRC (biologists involved in Project H), and Arizona State University.

Investigators 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 the Lees Ferry creel and in collaboration with AGFD.

Project Element J.3. Recreation Monitoring and Research

Implementation of surveys related to Project Element J.3 will be coordinated with assistance of AGFD and GCNP. Angler intercept surveys, as part of the AGFD creel, are ongoing, and GCNP maintains a list of private whitewater boaters. Past research collaboration with both AGFD and GCNP have proven to be productive (Bair and others, 2016; Neher and others, 2017).

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7. Budget

Fiscal Year 2021								
Project J Socioeconomic Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							14.00%	
J.1. Predictive models for adaptive management	$48,118	$1,500	$250	$0	$10,500	$0	$7,297	**$67,664**
J.2. Brown trout incentivized harvest	$74,028	$2,500	$1,250	$0	$50,500	$0	$12,404	**$140,681**
Total Project J	**$122,145**	**$4,000**	**$1,500**	**$0**	**$61,000**	**$0**	**$19,700**	**$208,346**

Fiscal Year 2022								
Project J Socioeconomic Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							22.00%	
J.1. Predictive models for adaptive management	$49,080	$1,500	$250	$0	$0	$0	$11,183	**$62,013**
J.2. Brown trout incentivized harvest	$75,508	$1,500	$1,250	$0	$45,500	$0	$18,582	**$142,340**
Total Project J	**$124,588**	**$3,000**	**$1,500**	**$0**	**$45,500**	**$0**	**$29,764**	**$204,353**

Fiscal Year 2023								
Project J Socioeconomic Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
J.1. Predictive models for adaptive management	$49,512	$1,500	$250	$0	$0	$0	$14,353	**$65,615**
J.2. Brown trout incentivized harvest	$77,018	$1,500	$1,250	$0	$24,500	$0	$23,070	**$127,338**
Total Project J	**$126,530**	**$3,000**	**$1,500**	**$0**	**$24,500**	**$0**	**$37,423**	**$192,953**

8. Experimental Project Budget

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 experimental event. It is expected that one recreational survey a year will occur in accordance with an experimental flow.

See budget table in Experimental Project Fund Appendices.

Project K: Geospatial Science, Data Management and Technology

1. Investigators

Thomas M. Gushue, IT Specialist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
James W. Hensleigh, IT Specialist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center
TBD, Geographer, 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 US Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (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. While some of the work elements described within this project discuss the use of newer technologies and methods for managing, analyzing and providing access to the Center's data resources, the concepts that this work serves are not new and have been part of the GCDAMP since the beginning. By standardizing our data resources, streamlining workflows and leveraging new technologies, we can fulfill these important needs of the program more efficiently, and ultimately, for much lower costs than would occur if each project would be left to develop their own closed systems. 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, 2016a, b).

3. Hypotheses and Science Questions

Project K does not address specific science questions or hypotheses as it is inherently a supportive effort for GCDAMP-funded projects and a Center-wide resource for geospatial and data management functions. However, this project delivers critical support across GCMRC including services such as data processing, data management and documentation, and geospatial processing and analysis which are essential to the success of nearly all projects. The following justifications have been used to guide this work plan proposal:

- Data management, including geographic information systems (GIS), has been a part of GCMRC's role in GCDAMP since its inception, and was also supported in the 1995 ROD – specifically in GCDAMP Goal 12, to maintain a high-quality monitoring, research and adaptive management program (U.S. Department of Interior, 1996).
- Subsequent documents, including the most recent LTEMP, have reaffirmed this important aspect of GCMRC and the adaptive management program (U.S. Department of Interior, 2016a).
- Project K is designed to support the other proposed science projects that are aligned with resource goals identified in the LTEMP and in more recent DOI guidance where both documents call for continuity in resource monitoring and consistency in providing high-quality monitoring and research to the Adaptive Management Program (U.S. Department of Interior, 2016a; Petty, 2019).
- Project K works to share important information about trends in resources of the Colorado River ecosystem through web-based, interactive tools and mapping products (VanderKooi and others, 2017).
- Project K allows for the ability to make better informed, time-sensitive decisions on experimental and management actions under the 2016 LTEMP and the associated ROD (U.S. Department of Interior, 2016a, b).

4. Background

There exists a long legacy of monitoring and research data being collected in support of science focused on studying effects of Glen Canyon Dam operations dating back more than 30 years. These data were often disparate between different science projects and certainly between studies focused on different resource types. Initial attempts to build one, all-encompassing relational database were valiant; however, complexities inherent in that approach proved to be insurmountable as individual resource monitoring efforts changed, expanded and morphed into different entities with different data requirements. Trends in data management, information technologies and programming has made it possible to move away from this concept over the last two triennial work plans. Only in recent years, with the adoption of more modern GIS and database software, and advancements in data sharing capabilities, has the scope of our research been able to become more integrated across disciplines and among different research efforts. The fact that this can be achieved without trying to maintain one, very complex database is a benefit to our future work for the GCDAMP.

Data management in support of research and monitoring has been a part of GCMRC since its inception and was specifically outlined in the 1995 Environmental Impact Statement that clearly defines the Center's responsibilities for managing data in support of the GCDAMP (U.S. Department of Interior, 1995). The concept of data management encompasses many facets including, but not limited to, data preservation, design, development and maintenance of systems and applications designed to store and serve the data, building 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. Success of 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 (U.S. Department of Interior, 2016a).

GCMRC has experienced some large shifts in how its data resources have been managed. These shifts have often reflected major organization changes imposed upon the Center – both internal and external. Examples of these events include the creation of the Southwest Biological Science Center in 2005 and eventual deconstruction of the original Information Technology program, and somewhat similarly, the disbanding of GCMRC's program structure altogether in 2013. Such events do have implications on how a long-term monitoring program continues to maintain consistency in its data resources. One implication from both events was the decentralization of scientific data, and the rise of independent project-driven data sets. There are consequences of not standardizing our data management practices. Many issues arise if science project staff are charged with performing all data management tasks solely on their own. Inefficiencies in data storage, data access, and analytical abilities can occur due to decisions made within a specific project as to the data organization, software used to process the data, and separate workflows developed for accessing the data. These inefficiencies translate into higher costs incurred through project staff salary that spend additional time trying to manage and work with their data, and these higher costs become magnified when applied across multiple projects. Data loss is likely to happen as turnover in science project staff occurs regularly even throughout a 3-year work plan and certainly more so for longer periods of time within LTEMP. This may compromise GCMRC's ability to efficiently and effectively address the larger questions being asked, such as the 10-year assessment that is called for in the LTEMP ROD (U.S. Department of Interior, 2016b; VanderKooi and others, 2017).

While this project is still adhering to its role as the lead in GIS application to science projects, additional roles have also accumulated as natural extensions to the geospatial science work over the past few years. The functions of data management were previously addressed within the Data Acquisition, Storage, and Analysis (DASA) program; however, since the reorganization of GCMRC in 2013 away from resource programs and towards a new, project-oriented focus, data management responsibilities are no longer centralized for the Center. Because of this reorganization, positions that traditionally focused primarily on GIS support have had to expand their roles to include data management oversight, as well as providing computer systems expertise, web server and internet technology leadership, the design, development and deployment of technologically-advanced scientific monitoring equipment and, most recently, the adoption of a hybrid-cloud data storage model and hosted application services. Some of this capacity has existed within GCMRC in previous work plan cycles but is now being described more holistically within the context of a work plan. The project elements presented in Section 5 of this project proposal describe this increased capacity more fully.

In addition to its commitment to the GCDAMP and LTEMP, the GCMRC, as a part of the USGS, must comply with federal guidelines governing many aspects of how geospatial data are collected and maintained by the Center. These aspects range from how specific data are to be collected, to accuracy standards established through federal policy – Federal Geographic Data Committee (FCDC), National Standard for Spatial Data Accuracy (FGDC, 1998), to how data are to be reviewed and released in conjunction with peer-reviewed scientific publications. This last concept is relatively new and is more fully described by the most recent USGS Fundamental Science Practices in response to an Executive Order that redefined the data release policies of federal agencies (U.S. Geological Survey, 2017). As the Geospatial Science project has increased its role in assisting with proper data management for the Center, work performed in this project will continue to lead efforts for adhering to these requirements.

5. Proposed Work

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

Thomas M. Gushue, IT Specialist, USGS, GCMRC
TBD, Geographer, USGS, GCMRC
James Hensleigh, IT Specialist, USGS, GCMRC

Work performed within this Element will continue to provide the same 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 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.

GIS Support to GCDAMP-funded Projects

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 FY2018-20 TWP is processing and analysis work on the Glen Canyon channel map data set (U.S. Department of Interior, 2017). Specific tasks performed by GIS staff included processing derived data sets from the 2013 Digital Surface Model (DSM) to remove vegetation from the data, 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 (Figure 1). This work directly benefitted Project B's Sandbar and Sediment Storage work by contributing to a deliverable. The resultant data set also supported Project H, Salmonid Monitoring and Research, and more specifically, Project Element H.1, by supplying slope characteristics derived from the full channel DEM to be used in Trout Management Flow analysis.

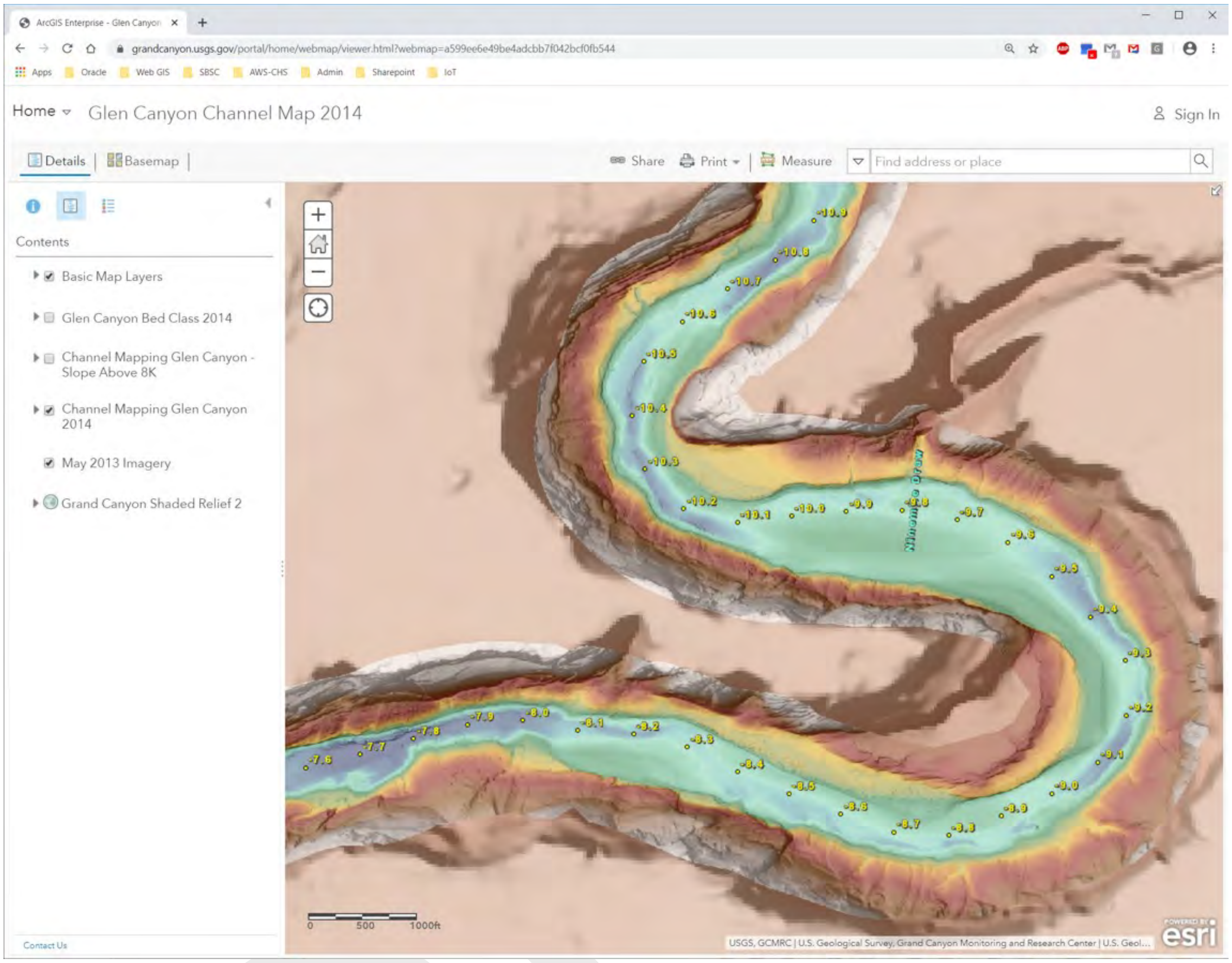

Figure 1. View of online map of Glen Canyon channel map Digital Elevation Model (DEM) and shaded relief using a multi-directional hillshade algorithm. Data shown is of Horseshoe Bend in Glen Canyon (River Mile -9, Colorado River).

The process for determining higher-level GIS support to projects in this TWP began with informal discussions with other GCMRC principal investigators as early as FY2019. Beginning in FY2020, more focused discussions occurred, and regularly scheduled meetings were held for all PIs since January 2020, providing opportunities for larger requests of Project K to be brought forward. Through additional consultation with principal investigators on specific resources and valuable feedback from the Technical Work Group (TWG) and more specifically, the Budget Ad-Hoc Group (BAHG) of the TWG, the large requests for GIS support have been condensed to provide a view of the needs for the Center (Table 1) that will require some significant amount of time (2 pay periods or more) from Project K staff.

Table 1. Proposed large geospatial support tasks efforts for specific projects described in this work plan.

Project	Project element	Support description
B. Sandbar and Sediment Storage	B.1. Sandbar and Campsite Monitoring	· Provide GIS and mapping expertise to sandbar and campsite monitoring efforts. · Continued involvement and maintenance of sandbar database and online application · Expanded effort to support remote camera image processing to delineate sandbar area.
	B.2. Bathymetric and Topographic Mapping	· Provide GIS and mapping expertise to channel mapping data collection efforts. · Improve on previously developed methods for mosaicking airborne Digital Surface Model (DSM) data with channel mapping data.
	B.3. Control Network and Survey	· Continued GIS support to control network and survey operations. · Geospatial data processing and analysis associated with implementing the North American Terrestrial Reference Frame of 2022 (NATRF2022).
	B.5. Streamflow and Sandbar Modeling	· Geospatial data processing and analysis in support of streamflow modelling issues. · GIS layer development, data preparation and review for publication.
C. Riparian Vegetation	C.1. Ground-based riparian vegetation monitoring	· Work with scientist to develop data visualization tools driven by back-end database. · Develop online web mapping application highlighting vegetation monitoring data over time.
L. Overflight	L.1. Overflight remote sensing	· Provide experience and expertise to mission planning and implementation of remote sensing overflight data acquisition.

Enterprise GIS

Work within this project has strived to improve access to geospatial data resources over the previous two triennial work plans (U.S. Department of Interior, 2017; Bureau of Reclamation, 2014). This work has been supported in both the LTEMP ROD and the related science plan where the GCDAMP calls for continued and, in some cases, improved access to geospatial and scientific data pertaining to important riparian resources (VanderKooi and other, 2017). To meet this need, Project K maintains an enterprise GIS platform that is built upon Environmental Systems Research Institute (ESRI) ArcGIS Enterprise (ESRI, 2020a) 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 FY2021-23 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. This Enterprise GIS consists of an internal Oracle spatial database as the back-end architecture for storing and serving geospatial data within the USGS internal network. The ArcGIS Server component is then used to build web-based services for the data sets stored in the Oracle database. Internal, desktop GIS users can access the Oracle data sets directly, if desired, while both internal and external clients can connect to the data services managed through ArcGIS Server. The third component of this Enterprise GIS system is Portal for ArcGIS. Portal is an online, content management system for geospatial data, and the GCMRC GIS group has maintained this online platform since 2013.

GCMRC Portal URL link: https://grandcanyon.usgs.gov/portal/home/index.html

ArcGIS Online

The Geospatial project has also worked to leverage outside, cloud-based platforms for creating greater access to GCMRC geospatial data. The most widely used example of this is GCMRC's presence on ESRI's ArcGIS Online content management system. ArcGIS Online is essentially a cloud-based version of the internal Portal that GCMRC maintains on-premise. The power of this system architecture is realized when considering that the data stored internally in GCMRC's Oracle database and served externally through ArcGIS Server can be simultaneously accessed through numerous maps and applications on both the internal Portal website and the external ArcGIS Online data serving platform (Figure 2).

URL link to GCMRC GIS on ArcGIS Online:
https://www.arcgis.com/home/search.html?q=GCMRC&t=content&restrict=false

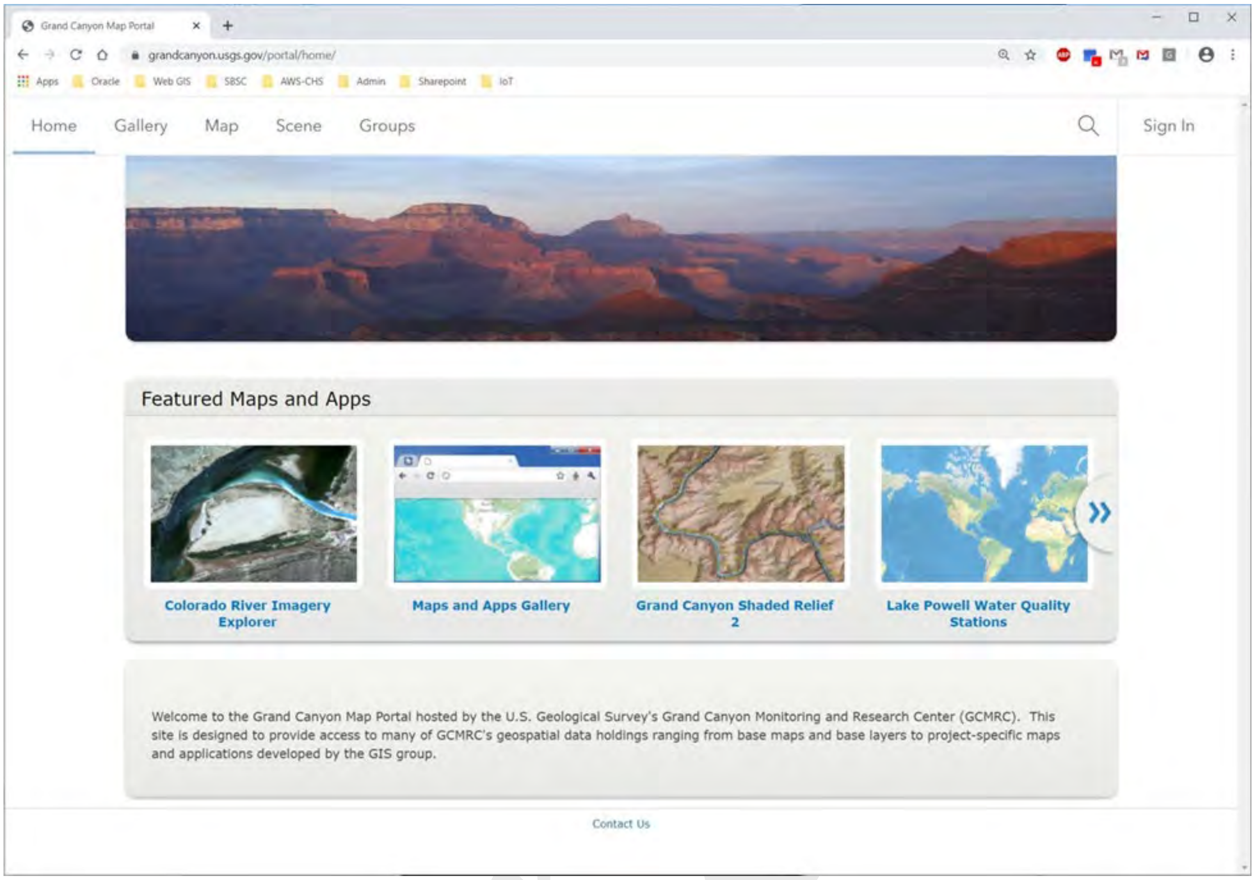

Figure 2. A screenshot of the Grand Canyon Map Portal website that serves geospatial data in the form of data services, online maps and custom web applications.

Additional GIS administration tasks related to science support included 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 K staff also provide oversight, direction and coordination to SBSC's information technology staff to ensure that the specific needs of GCMRC science staff are sufficiently met in a timely manner. Additionally, the principal investigator of this project networks with other entities across the USGS to help align the GCDAMP-funded work with on-going and new initiatives within the agency. Examples of this coordination include serving on the USGS Ecosystem Mission Area (EMA) Information Technology Advisory Council (ITAC) and serving on the GIS Remedy help desk team with the USGS Office of Enterprise Information (OEI), Enterprise GIS (EGIS).

Project Element K.2. Data Management and Database Administration

Thomas M. Gushue, IT Specialist, USGS, GCMRC
James Hensleigh, IT Specialist, USGS, GCMRC

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

Data management for GCMRC has existed in many different forms over the past 30 years. Advancements over the last two triennial work plans have positioned this project with expanding the use of relational databases, standardizing data management practices, and maintaining more efficient workflows working with data.

Individual science projects currently lack the expertise to sufficiently build and maintain enterprise-level databases and data sets that are necessary products for the GCMRC as the science provider for the GCDAMP. This project will continue to assume a larger role in all aspects of data management for the Center. This work includes consultation with USGS IT staff at many levels in the organization to ensure the proper systems exist for storage, archiving, retrieval and network access to the data by GCMRC staff. While scientists do currently have some discretion as to how their data are organized and processed, the systems provided are centralized on a modern disk array that has a 750-terabyte capacity and we employ a scheduled, cumulative backup strategy (daily, weekly, monthly) across all accessible network drives. Additionally, we utilize an off-site storage facility to maintain monthly backups for disaster recovery purposes.

This project will also continue to lead the Center in the development of new or improved relational databases that will more efficiently handle scientific data collected by other projects. Several resource areas have been identified as having insufficient capacity for properly storing and maintaining their data in a consistent and logical manner. In some cases, project-related data only exist in simple spreadsheet formats, with no efficient way to compile, analyze, share and provide reporting on specific GCDAMP-funded research efforts. Moving beyond the main focus of geospatial data, this project is poised to further assist with full database development for individual science projects currently lacking relational database support, and that are in dire need of better data storage, analysis, and access capabilities. Additionally, this project will initiate more advanced data processing and computational power through a data processing server that which has been configured to maximize the number of Central Processing Units (CPUs) made available to an end user for complex processing jobs. Additionally, this system leverages server-hosted application technology that can deploy applications and software from more powerful computer servers to the end users' desktops and laptops. This processing environment is now currently designed for advanced geospatial analysis and better performance on model processing conducted by GCMRC scientists.

Members of this project also serve as liaisons to the USGS data review process (Section 3) for GCMRC projects with complex geospatial components or that are leveraging relational databases for data storage. This work may involve assisting and training staff in metadata development, data management plan creation and adherence, and other work related to the data publication process. Additionally, this project will lead an effort for better implementation of source control procedures for project-based data processing, scripting and program development, software design and development, and development of web-based applications.

Database Administration

Work proposed within this project element include the continued maintenance of existing relational databases in support of LTEMP 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, Overflight Imagery, and Lake Powell Water Quality.

For the FY2021-23 TWP, the primary focus will be on the full documentation, redesign and re-implementation, where necessary, of the existing fish monitoring database and workflow. The fish monitoring database is one of the most important data resources maintained by GCMRC. Project K is now better positioned to greatly improve the entire workflow process for storing, reviewing, analyzing and accessing fish aquatic information. The migration of project data to relational databases began during the past two triennial work plans (Bureau of Reclamation, 2014; U.S. Department of Interior, 2017). This next 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.

Table 2. List of resources and projects (using FY2021-23 project names) with associated relational databases developed over last two triennial work plans (FY2015-17, FY2018-20).

Project	Project element	Support description
B. Sandbar and Sediment Storage	B.1. Sandbar Monitoring	· Database to maintain sandbar area and volume data. · Has online component that is hosted in AWS cloud.
	B.3. Control Network and Survey	· Geodetic Network Control Database and Create, Read, Updated, and Delete (CRUD) application. · Online component to be available by end of FY2020.
C. Riparian Vegetation Monitoring	C.1. Ground-based riparian vegetation monitoring	· Riparian Vegetation Monitoring Database and Create, Read, Updated, and Delete (CRUD) application.
Lake Powell	Water quality monitoring	· Lake Powell Water Quality Monitoring Database and Create, Read, Updated, and Delete (CRUD) application.

Cloud-based Resources

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. Leveraging cloud technology within this project element and in K.3. Remote Monitoring and Advanced Technology Support will assist with the tasks of assessing and reporting on conditions of the riparian resources that is being asked of GCMRC.

Table 3. Proposed major database administration support efforts for specific projects described in this work plan.

Project	Project element	Support description
G. Humpback Chub Population Dynamics	G.1. Humpback chub population modeling	· Work with project scientists to improve data workflow for running population models from standardized database. · Research and provide expertise on high-performance computing (HPC) technologies.
	G.2. Humpback chub abundance estimates, lower LCR	· Work with co-operators (USFWS) and GCMRC staff to import data into database. · Look to improve workflows for importing and accessing database.
	G.3. Juvenile chub monitoring	· Work with GCMRC staff to import data into database. · Look to improve workflows for importing and accessing database.
	G.4. Remote PIT tag array monitoring in the LCR	· As data becomes available to cloud resources, work with scientist to access and process data.
	G.5. Monitoring Humpback chub aggregation	· Work with GCMRC staff to import data into database. · Look to improve workflows for importing and accessing database.
Lake Powell	Water quality monitoring	· Maintenance of relational database that was redesigned and implemented in FY2019-20. · Support with data release and Open-file report.

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

Thomas M. Gushue, IT Specialist, USGS, GCMRC
Timothy Andrews, Physical Scientist, USGS, GCMRC

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. Currently, several projects rely on remote monitoring sensors for acquiring timely and necessary data that are required for addressing the questions and concerns about specific resources of the Colorado River ecosystem. The maturity of these systems vary widely across resources and therefore individual project and project elements. A need exists to continue to maintain those systems that the GCDAMP has also relied on for making timely, informed management decisions, while also expanding and improving upon the use of sensors to allow for cost-effective data streams that future science and management decisions will depend upon in the future. This work is not meant to bloat the science center, but rather make it a more efficient engine for responding to the needs of the GCDAMP.

Modernizing Field-based Sensors

In FY2017, 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 gaging station (River Mile 0) as of January 2020 (Figure 3).

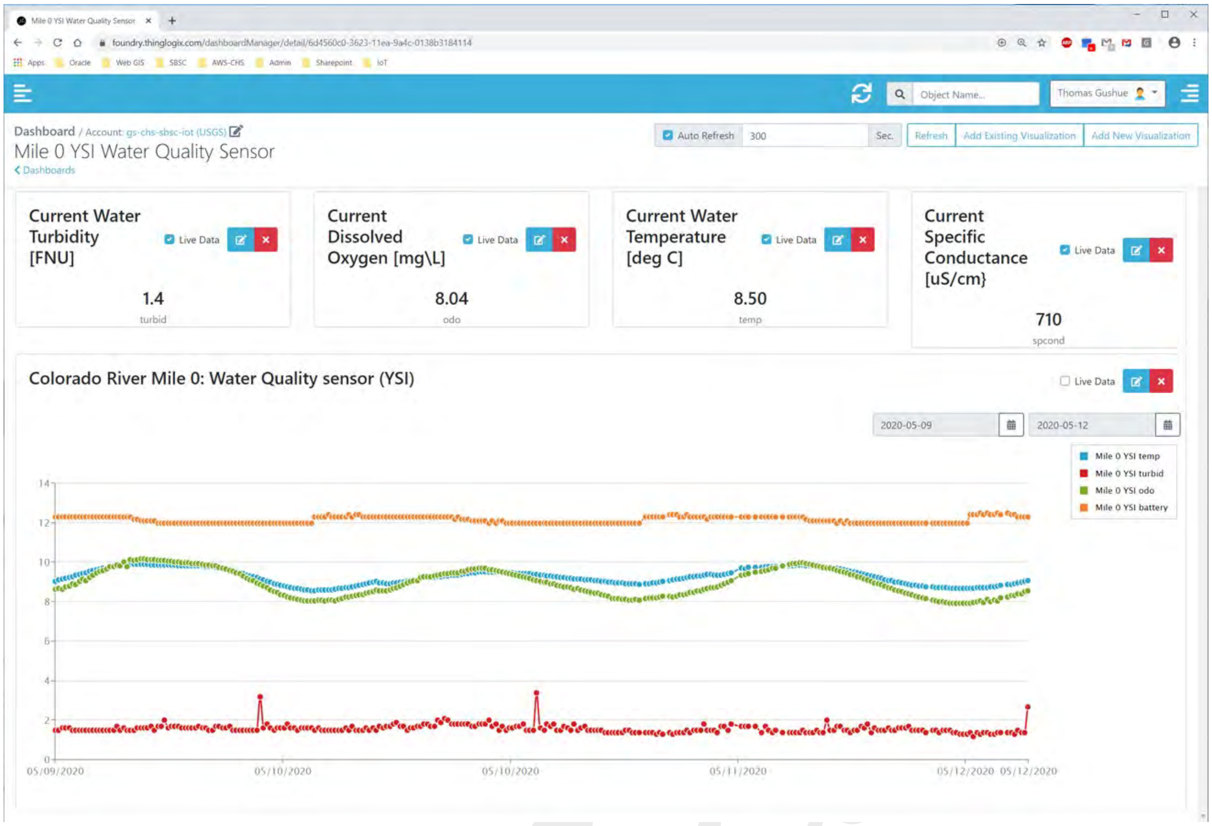

Figure 3. A screenshot of a custom data dashboard for the water quality sensor located at the Lees Ferry gaging station (River Mile 0, Colorado River).

The objective for continuing this work into FY2021-23 is to modernize the existing sensors through the 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 GCMRC as a whole by improving upon the design and development of common components used by most remote monitoring systems deployed by GCMRC.

GCDAMP-funded Project Support

Contained here is an outlined list of resource-specific projects that have been supported through this element in past triennial work plans and are expected to continue into the next triennial work plan.

Table 4. Proposed remote monitoring support efforts for specific projects described in this work plan.

Project	Project element	Support description
A. Streamflow, Water Quality, and Sediment Transport	A.2. Continuous water quality parameters	· Maintain hardware and software on remote monitoring stations for water quality sensors in Glen Canyon · Work with scientists on accessing data and creating workflows on cloud platform
	A.3. Sediment transport	· Train project staff on proper maintenance of hardware and software on remote monitoring stations for sediment mass budget · Computer programming expertise for Satellite Control program
B. Sandbar and Sediment Storage	B.1. Sandbar and Campsite Monitoring	· Investigate feasibility of processing images through Amazon Web Services (AWS) cloud resources, possibly utilizing edge computing workflows, where possible
	G.4. Remote PIT tag array monitoring in the LCR	· Maintain system for sending data from two fish antenna systems: a multiplexer system (MUX) and a network of shore-based single antennas (NET) via cellular communication to GCMRC's cloud resources on AWS. · Computer programming expertise for communicating with remote systems · Troubleshooting and resolving hardware and operating system issues · Work with scientist on developing methods for accessing data from system.

Important resources which can now be monitored remotely include streamflow, sediment transport, water quality, sandbars through remote cameras, and humpback chub in the Little Colorado River. While some projects have decided to outsource the management of their data and online applications (Project A), all projects with remote monitoring aspects have come to rely on support within this project for some or all of the work in maintaining these systems. This reliance is expected to increase in the next TWP; however, by building upon existing knowledge of this work and leveraging new, cloud-based capabilities we can begin to see the benefits of near real-time data acquisition at reduced costs when compared to other existing telemetry applications.

5.2. Outcomes and Products

Project Element K.1.

Outcomes:

- More comprehensive Enterprise GIS platform, better online analytical capabilities, expansion of canyon-wide geospatial data releases and better access to data.

Products:

- Geospatial data sets, metadata documents, and map outputs in various forms in support of other projects, online web services that include data layers, interactive maps and custom web applications, published data releases, and publications related to some elements of this work.

Project Element K.2.

Outcomes:

- Improved, more efficient workflows for specific, project-based data resources, improved access to data resources for managers, stakeholders and the public.

Products:

- Project-specific relational databases, and associated applications and software for interaction with those databases, documentation of standardized processes, source control workspaces, wikis, and publications related to these work elements.

Project Element K.3.

Outcomes:

- Improved access to important scientific data about specific resources and parameters

Products:

- Online data visualizations of near real-time data for water quality and other parameters, two-way communication access for scientists to field-based sensors, ability for stakeholders and others to subscribe to alerts based on user-provided thresholds.

5.3. Personnel and Collaborations

Thomas M. Gushue, IT Specialist, is the principal investigator of this project and has served as the GIS Coordinator of GCMRC since 2005. James W. Hensleigh, IT Specialist, first joined GCMRC in 2016 as a Geographer within the GIS Project and now serves as GCMRC's new Database Administrator. Timothy Andrews, Physical Scientist, has been with GCMRC since 2004 in various roles, and joined as a USGS employee in 2010. Another Geographer is expected to be hired in FY2020 to fill the position vacated by James Hensleigh this year. In addition to the collaborations with other proposed projects defined in this TWP (Tables 1-4), staff within this Project have several key collaborations occurring outside the GCMRC. These include membership in certain focus groups (USGS Cloud Hosting Solutions, USGS Tableau User Group, USGS High-Performance Computing User Group) and leadership roles within the agency (member of USGS Ecosystem Mission Area Information Technology Advisory Council), and collectively as a pilot program for USGS Cloud Processing Framework and the emerging USGS initiative EarthMAP (Earth Mapping, Analysis, and Processing).

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7. Budget

Fiscal Year 2021								
Project K Geospatial Science, Data Management and Technology Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
K.1. Geospatial science	$147,535	$2,303	$2,400	$0	$0	$0	$21,313	**$173,552**
K.2. Database management	$122,806	$2,303	$700	$0	$0	$0	$17,613	**$143,423**
K.3. Remote monitoring and advanced technology	$90,739	$500	$3,000	$0	$0	$0	$13,193	**$107,433**
Total Project K	**$361,081**	**$5,107**	**$6,100**	**$0**	**$0**	**$0**	**$52,120**	**$424,408**

Fiscal Year 2022								
Project K Geospatial Science, Data Management and Technology Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
K.1. Geospatial science	$191,141	$2,470	$1,400	$0	$0	$0	$42,903	**$237,914**
K.2. Database management	$144,724	$2,470	$700	$0	$0	$0	$32,537	**$180,431**
K.3. Remote monitoring and advanced technology	$35,106	$500	$2,050	$0	$0	$0	$8,284	**$45,940**
Total Project K	**$370,971**	**$5,440**	**$4,150**	**$0**	**$0**	**$0**	**$83,723**	**$464,284**

Fiscal Year 2023								
Project K Geospatial Science, Data Management and Technology Project	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
K.1. Geospatial science	$184,541	$1,637	$1,400	$0	$0	$0	$52,522	**$240,099**
K.2. Database management	$161,242	$1,637	$700	$0	$0	$0	$45,802	**$209,381**
K.3. Remote monitoring and advanced technology	$46,231	$500	$1,600	$0	$0	$0	$13,533	**$61,864**
Total Project K	**$392,014**	**$3,774**	**$3,700**	**$0**	**$0**	**$0**	**$111,857**	**$511,344**

Project L: Overflight Remote Sensing in Support of GCDAMP and LTEMP

1. Investigators

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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 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 FY2021-23 Triennial Work Plan (TWP). The data sets derived from remote sensing overflights (Table 1 and Figure 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 Plan (LTEMP; U.S. Department of Interior, 2016a). Data derived from the 2021 overflights will be used in the LTEMP Record of Decision (ROD) implementation process (U.S. Department of Interior, 2016b).

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, system-wide remotely-sensed data are necessary to complement ground-based data collection and assist with the GCMRC'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 FY2021-23 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 (GCDAMP) on performance of the LTEMP ROD.

3. Science Questions

Project Element L.1.

Science Questions:

- How has landcover changed in the Colorado River ecosystem in 2021 relative to preceding decades?
- How are observed landcover changes related to dam operations, other land use and management activities, as well as climate and other environmental factors in the ecosystem?

4. Background

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. Table 1 lists the primary datasets from overflight missions and the derivative products used by science projects to address resource goals. Table 1 also provides links to recent examples of these datasets and products.

In 2002, 2005, 2009, and 2013, GCMRC, through the GCDAMP, acquired digital, 4-band multispectral imagery and photogrammetrically derived topography data similar to the data proposed in this project to be acquired in 2021. With each of those previous digital image acquisitions, GCMRC remote sensing staff developed and improved upon a methodology for producing a spatially seamless, spectrally consistent, and nearly cloud- and blemish-free image mosaic (Davis and others, 2012; Durning and others, 2016; Table 1). That proven methodology will be used to develop an image mosaic from the 2021 acquisition.

Table 1. Summary of primary datasets and examples of derived products from overflight missions used by Glen Canyon Dam Adaptive Management Program science projects to achieve Long-Term Experimental and Management Plan resource goals. Please follow hyperlinks for examples.

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 (Figure 1) · Publication maps
Fish sampling unit system for the mainstem Colorado River (Figure 1)	Adult and juvenile humpback chub and monitoring system for the 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.

Image mosaics from overflight missions have myriad uses that are critical to different aspects of most of the science implemented through the GCDAMP. Perhaps most importantly, the mosaics are the base map layer for all map books used by science projects to navigate the river and implement field monitoring and research campaigns (Table 1 and Figure 1). Image mosaics from previous overflights are also used to produce website content and online Geographic Information Systems (GIS) maps, such as the GCMRC GIS Base Map Viewer (Table 1).

Many science projects develop detailed study designs in GIS with the imagery. Examples of such study designs include the fish sampling unit system for the mainstem Colorado River, and the adult and juvenile humpback chub monitoring system for the Little Colorado River (Table 1 and Figure 1). Measurements of important river channel characteristics that change over time are periodically updated using the most current overflight imagery. For example, the river-channel mileage system published by GCMRC and used to navigate and monitor the river, is based on the centerline of the river channel delineated on the published overflight image mosaic data (Table 1; Gushue, 2019).

Once the 2013 overflight image mosaic was published, GCMRC developed a workflow for producing landcover classification maps derived from that mosaic. The workflow progressed by first publishing the most basic, fundamental maps of landcover including the low-flow river channel at 8,000 ft^3/s (i.e., landcover class of water; Durning and others, 2017a), sand and other river sediment (Sankey and others, 2018c), and total vegetation (Table 1; Durning and others, 2017b). Once those landcover maps were published, GCMRC remote sensing staff next produced more detailed classification maps for riparian vegetation differentiated by species (Bedford and others, 2018a; Durning and others, 2018). Remote sensing staff then collaborated with other GCMRC project staff to leverage the landcover classifications, imagery, and topographic data for science that relates decadal-scale observations of landcover in the Colorado River ecosystem to dam operations, other land use and management activities, climate and other environmental factors.

One example of this higher-order science leveraged from overflight data is the quantitative assessment of riparian vegetation changes that occurred as a function of dam operations and climate during the first five decades of the operations of Glen Canyon Dam published by Sankey and others (2015). Another example are quantitative inventories of tamarisk and tamarisk beetle impacts in Glen Canyon by Sankey and others (2016) and in Grand Canyon by Bedford and others (2018b) and Bransky (2020). Bransky (2020) determined that high-resolution, Worldview satellite imagery acquired in 2019 could not be used to produce an image mosaic and species classification of tamarisk in Grand Canyon as accurate as that produced with the 2013 overflight imagery by Bedford and others (2018b). However, Bransky (2020) was able to use the combination of satellite and overflight imagery to assess tamarisk beetle impacts at the stand level from 2013 to 2019.

Hadley and others (2018) used the landcover classifications derived from the imagery to help quantify changes in campsites along the river. Sankey and others (2018a, b) used overflight imagery and topography to assess effects of dam operations on source-bordering aeolian dunefields that house archaeological sites in Grand Canyon. Kasprak and others (2017a, b) used overflight imagery and topography to develop a method for automating the interpretation of repeat survey data in river valleys. Kasprak and others (2018) used overflight imagery, topography, and landcover classifications to model the combined influence of changes in river flow and riparian vegetation on the areal extent of sediment available for transport in Grand Canyon from 1921 to 2016, as well as to forecast changes from 2016 to 2036. Kasprak and others (2019) used overflight imagery and ground-based photogrammetry and lidar to survey sandbars and sand dunes. Recently, Butterfield and others (2020) leveraged the species-level classification of Durning and others (2018) to analyze associations between riparian plant morphological guilds and fluvial sediment dynamics in Grand Canyon.

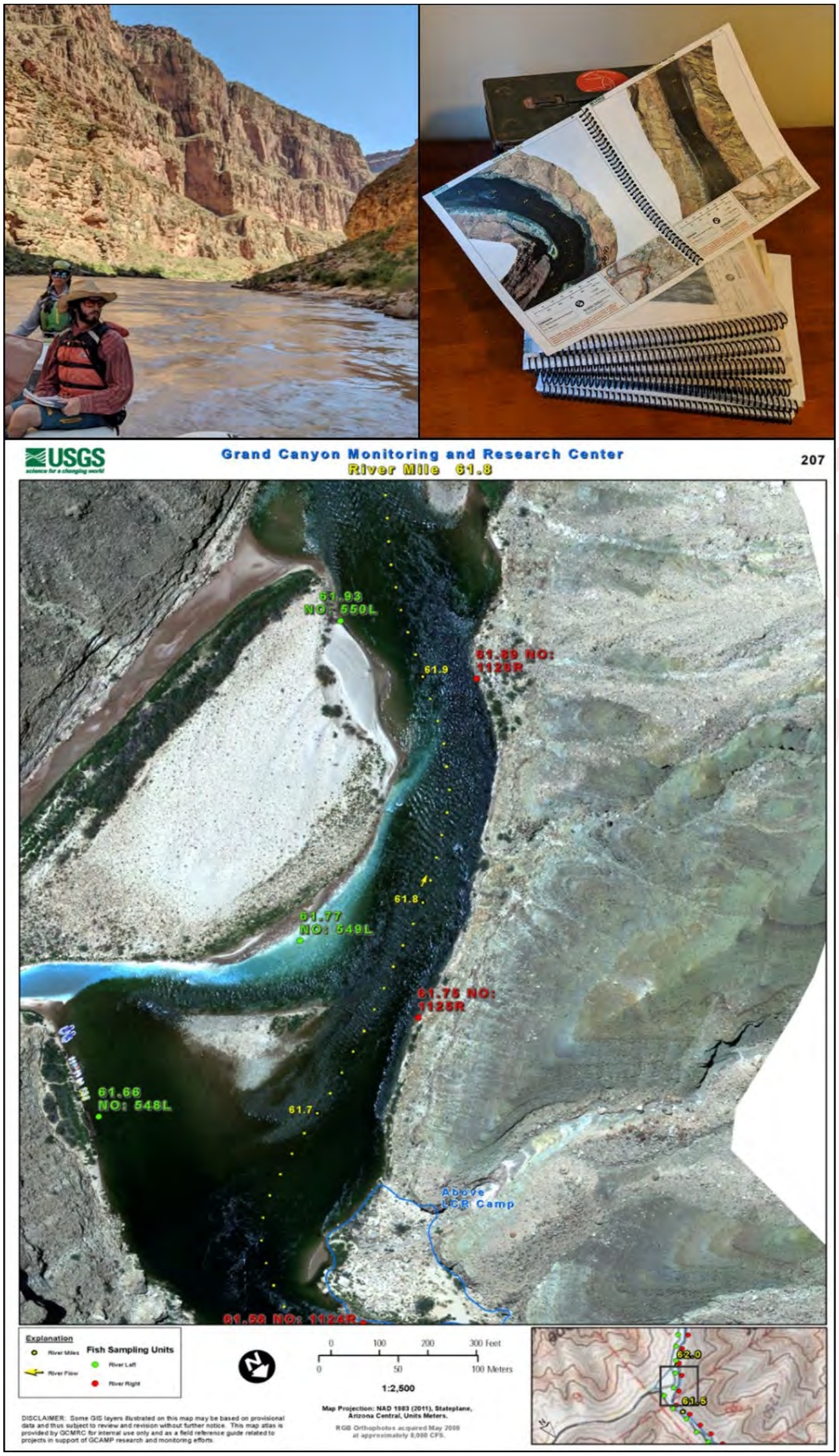

Figure 1. Remote sensing imagery are the base map layer for all map books used by science projects to navigate the river and implement field monitoring and research campaigns. The top left photo shows a scientist consulting his map book on the river. The top right photo shows a stack of map books printed for a recent field campaign. The bottom panel shows a page of a map book with Fish Sampling Units delineated for a recent monitoring campaign.

5. Proposed Work

Project Elements

Project Element L.1. Overflight Remote Sensing

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Keith Kohl, Surveyor, USGS, GCMRC
Laura Durning, NAU

GCMRC will implement a remote sensing overflight to collect digital, multispectral imagery and topography of the Colorado River ecosystem between Glen Canyon Dam and Lake Mead in May 2021. To maintain consistency with previously collected digital, orthorectified aerial imagery acquired in 2002, 2009, and 2013 (Davis, 2012; Durning and others, 2016), the mission will be conducted during the same time of year (beginning on Memorial Day weekend and lasting for potentially one week or longer depending on weather) 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 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 to be written by GCMRC scientists in FY2021 (i.e., first year of the FY2021-23 TWP), 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 and maximizes subaerial terrain that is not inundated by the river in the imagery. This will allow for highly accurate image classification of landcover in May 2021, and for image matching and change detection analysis with previous overflight datasets (see for example: Sankey and others, 2015, 2018a, c; Bedford and others, 2018b; Kasprak and others, 2018).

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 2021 mission. The LTEMP states that "triggers for a fall HFE would be met 77% of the years in the LTEMP period," and though spring sediment-triggered HFEs are probably even less likely, HFE effects are simply an important aspect of the river system that are observed via periodic remote sensing overflights.

This project will adhere to a well-defined sequence of project planning, data acquisition and analysis steps during the three years of the FY2021-23 TWP. The timeline and sequence of activities is summarized in Table 2. During the first quarter of FY2021, GCMRC staff from this project will write the Scope of Work (SOW) and negotiate the contract with the vendor for the overflight data acquisition. Next, during the second quarter of FY2021, project staff will plan the mission logistics. In addition to the imagery acquisition conducted by the vendor and overseen by GCMRC in May 2021, mission logistics will also include a rim-level operation during the overflight in which GCMRC will operate Geographic Positioning System (GPS) base stations on known survey control points throughout the canyon corridor. The GPS data from the rim-level operation will be used by the vendor to assess the accuracy and precision of the positioning of their airplane-mounted sensors.

There will also be river-level operations before, during, and after the overflight mission to:

1) Place ground-control targets on known survey control points throughout the corridor in advance of the overflight;
2) Conduct a long-profile survey of river elevation during the steady flow of the overflight;
3) Collect ground-truth data essential to calibrating and validating the image mosaic and landcover classification maps;
4) Remove the ground-control targets once the imagery acquisition is completed; and
5) Review preliminary data from the vendor, during the fourth quarter of FY2021, to assure and control for the quality of the final data.

Delivery of the final data is anticipated to occur at the end of FY2021. During FY2022, project staff will produce the image mosaic from the final data delivered by the vendor. In FY2022, GCMRC will publish the mosaic and then produce landcover classification maps to be used to answer the overarching science questions (stated above in section 3).

Table 2. Timeline of major activities and work effort for the overflight mission and remote sensing data analysis in Project L during the FY2021-23 Triennial Work Plan.

Fiscal Year	Quarter(s)	Activities
2021	1st	· Write Scope of Work and negotiate contract with vendor for overflight mission consisting of imagery and digital topographic data acquisition
	2nd	· Plan logistics for the overflight mission, including the rim- and river-level operations to be conducted by GCMRC in coordination with the vendor
	3rd	· Overflight mission; Rim-level GPS base station operations; River-level accuracy assessment and ground-truthing operations
	4th	· QA/QC performed by GCMRC in coordination with vendor; data delivered to GCMRC
2022	All	· Image mosaic built by GCMRC remote sensing staff
2023	All	· Image mosaic published; Landcover classification maps produced by GCMRC remote sensing staff

5.2. Outcomes and Products

Project Element L.1.

- Outcomes:
    - o 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 downstream to Lake Mead, and along the major tributaries to the Colorado River. The proposed schedule for this data collection mission is in May of 2021. The acquisition will occur at a low steady flow of 8,000 ft^3/s.

- Products:
  - o Imagery acquired in FY2021, mosaic produced in FY2022 and published in FY2023 (see Durning and others, 2016 for example of most recent mosaic published from the 2013 overflight).
  - o Landcover classification maps will be produced from the image mosaic during FY2023 (see Durning and others, 2017a, b; Sankey and others, 2018c; Bedford and others, 2018a; Durning and others, 2018 for examples of most recent landcover classification datasets published from the 2013 overflight).

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7. Budget

Note that the contract with the vendor for the overflight is estimated to cost $450,000 to image the river corridor from Glen Canyon Dam to Pearce Ferry (including the rapid which is downstream of the boat ramp). To pay for the contract, $150,000 was retained by Bureau of Reclamation from the current 5-year agreement, and GCMRC has identified $75,000 from FY2020 funding that will be carried over to 2021. Thus, Project L requires $225,000 in FY2021 to pay for the remainder of the contract (i.e., $450,000 - $150,000 - $75,000 = $225,000).

GCMRC is proposing to redirect and carry forward logistics funds from river trips cancelled due to the COVID-19 pandemic and associated closure of the Colorado River in Grand Canyon to help offset costs for the remainder of the contract. Also note that the budget is for an overflight that images the same geographic extent as the 2013 overflight. Arizona Game and Fish Department expressed an interest to GCMRC and Reclamation recently that the 2021 overflight should extend approximately another 50 river miles downstream of Pearce Ferry to South Cove in Lake Mead. We don't currently have funds to extend the data collection to South Cove but are looking for partners to share costs. It would cost an additional $50,000, raising the total estimated cost of the overflight contract to $500,000. We inquired with Reclamation and the Lower Colorado River Multi-Species Conservation Program about this, but a partner has not yet been identified.

Fiscal Year 2021								
Project L Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
L.1. Overflight remote sensing	$166,837	$3,000	$511,000	$33,493	$80,596	$0	$102,424	**$897,350**
Total Project L	**$166,837**	**$3,000**	**$511,000**	**$33,493**	**$80,596**	**$0**	**$102,424**	**$897,350**

Fiscal Year 2022								
Project L Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
L.1. Overflight remote sensing	$164,641	$0	$0	$0	$80,596	$0	$38,639	**$283,876**
Total Project L	**$164,641**	**$0**	**$0**	**$0**	**$80,596**	**$0**	**$38,639**	**$283,876**

Fiscal Year 2023								
Project L Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
L.1. Overflight remote sensing	$181,637	$0	$0	$0	$80,596	$0	$53,276	**$315,509**
Total Project L	**$181,637**	**$0**	**$0**	**$0**	**$80,596**	**$0**	**$53,276**	**$315,509**

Project M: Leadership, Management, and Support

The Leadership, Management, and Support budget covers salaries for a budget analyst, librarian, a part-time library assistant, three members of the logistics support staff, as well as leadership and management personnel for GCMRC. Leadership and management personnel salaries include those for the GCMRC Chief and Deputy Chief as well as half the salary for one Principal Investigator and half the salary for one 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 AMWG and TWG meetings. Cooperator funding is for support of the Partners in Science Program with Grand Canyon Youth. Operating expenses include:

1) GSA vehicle costs including monthly lease fees, mileage costs, and any costs for accidents and damage;
2) DOI vehicle costs including gas, maintenance, and replacements costs;
3) GCMRC's Information Technology equipment costs; and
4) A $20,000 annual contribution to the equipment and vehicles working capital fund.

Budget

Fiscal Year 2021								
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							14.00%	
M.1. Leadership, management, and support	$716,852	$30,000	$121,700	$0	$0	$0	$121,597	**$990,149**
M.2. Logistics staff	$264,218	$7,000	$0	$0	$11,000	$0	$38,301	**$320,519**
M.3. IT	$0	$0	$84,000	$0	$0	$0	$11,760	**$95,760**
Total Project M	**$981,070**	**$37,000**	**$205,700**	**$0**	**$11,000**	**$0**	**$171,658**	**$1,406,427**

Fiscal Year 2022								
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							22.00%	
M.1. Leadership, management, and support	$690,221	$20,000	$108,000	$0	$0	$0	$180,009	**$998,229**
M.2. Logistics staff	$269,502	$3,000	$0	$0	$11,000	$0	$60,281	**$343,783**
M.3. IT	$0	$0	$70,000	$0	$0	$0	$15,400	**$85,400**
Total Project M	**$959,723**	**$23,000**	**$178,000**	**$0**	**$11,000**	**$0**	**$255,689**	**$1,427,412**

Fiscal Year 2023								
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
M.1. Leadership, management, and support	$681,808	$20,000	$108,000	$0	$0	$0	$226,746	**$1,036,555**
M.2. Logistics staff	$273,839	$3,000	$0	$0	$11,000	$0	$77,845	**$365,684**
M.3. IT	$0	$0	$70,000	$0	$0	$0	$19,600	**$89,600**
Total Project M	**$955,648**	**$23,000**	**$178,000**	**$0**	**$11,000**	**$0**	**$324,191**	**$1,491,839**

Project N: Hydropower Monitoring and Research

1. Investigators

Lucas Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

2. Project Summary and Purpose

The Long-Term Experimental and Management Plan (LTEMP; U.S. Department of the Interior, 2016a) states that the objective of the hydropower and energy resource goal is to, "maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources." Project N will identify, coordinate, and collaborate with external partners on monitoring and research opportunities associated with operational experiments at Glen Canyon Dam designed to meet hydropower and energy resource objectives, as stated in the LTEMP Environmental Impact Statement (EIS) and its Record of Decision (ROD; U.S. Department of the interior, 2016a, b), and guided by the memorandum (Guidance Memo) from the Secretary's Designee, dated August 14, 2019 (Petty, 2019).

Operational experiments include proposed experiments in the LTEMP EIS (U.S. Department of Interior, 2016b), and other identified operational scenarios at Glen Canyon Dam to improve hydropower and energy resources, while consistent with improvement and long-term sustainability of other downstream resources. Project N will prioritize research associated with operational experiments at Glen Canyon Dam (GCD) designed to meet hydropower and energy resource objectives. Project N will also conduct monitoring and research of proposed experiments in the LTEMP EIS and consider impacts on hydropower and energy as part of the experimental design. Coordinated project implementation and development will occur between Reclamation, Western Area Power Administration (WAPA), and other collaborators to utilize and build on existing hydropower and energy models and data, specifically from Appendix K in the LTEMP EIS (U.S. Department of Interior, 2016b).

3. Hypotheses and Science Questions

Specific hypotheses and science questions to be addressed will be determined in coordination with Reclamation, WAPA, and other collaborators during Project N implementation and development.

4. Background

Project N will meet critical socioeconomic information needs identified by the GCDAMP (AMWG, 2012). Furthermore, the implementation of proposed experiments in the LTEMP EIS are, “contingent on the responses of one or more socioeconomic metrics” (VanderKooi and others, 2017). The role of the GCMRC, and its cooperators, is to provide information on physical and biological resources while also providing information related to socioeconomic aspects of resources, including hydropower (VanderKooi and others, 2017). Project N will focus on monitoring and research opportunities, utilizing past and ongoing research at GCMRC, Reclamation, and WAPA, to provide information related to the hydropower and energy objectives identified in the LTEMP ROD (U.S. Department of the Interior, 2016a) and the Guidance Memo.

A research element that is not included in this project is regional economic impact analyses. Regional economic impact analysis would inform the program and assist in the assessment of experimental operations at GCD (U.S. Department of the Interior, 2016b). The Long-Term Experimental and Management Plan Environment Impact Statement undertook regional economic impact analysis and found no significant impact in regard to operation of GCD, including proposed experiments, over the next 20 years. However, as the electricity sector changes, revisiting the regional economic impact of changes in operation at Glen Canyon Dam in future workplans may be warranted.

5. Proposed Work

Project Element N.1. Hydropower Monitoring and Research

Lucas Bair, Economist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Project N will identify, coordinate, and collaborate on design, monitoring, and research opportunities associated with all operational experiments at Glen Canyon Dam (GCD) to meet hydropower and energy resource objectives, as stated in the LTEMP ROD (U.S. Department of the Interior, 2016a). Operational experiments include experiments proposed in the LTEMP EIS and operations or experiments that improve hydropower and energy resources (e.g., change in ramp rates, change in daily flow range, fluctuating flow factors, and monthly volume patterns), while consistent with improvement and long-term sustainability of other downstream resources (Petty, 2019). Monitoring and research of hydropower and energy resources will be prioritized, in consultation and coordination with Reclamation, WAPA, and other collaborators, based on the sequence of proposed experiments in the LTEMP EIS (U.S. Department of Interior, 2016b), availability of predictive models to assess downstream resource conditions in response to experiments designed to improve hydropower and energy resources, and/or the magnitude of economic impacts of operational changes at GCD.

Development of GCD operational experiments during WY2021 – 2023

Investigators will work with GCMRC scientists, as they develop proposals for operational experiments, to incorporate the hydropower resource objective as an integral part of the experiment. For each experiment considered, investigators will coordinate with GCMRC scientists and WAPA technical staff throughout the process.

Macroinvertebrate Flows

Reclamation has conducted macroinvertebrate production flows (Bug Flows) during the summer months of 2018-2020. The purpose of this experiment is to identify how operations can improve the abundance, diversity, and stability of aquatic insect populations, thereby increasing aquatic foodbase for native fish, nonnative fish, and terrestrial wildlife in the Colorado River ecosystem. If these flows are judged to be beneficial to macroinvertebrates or successful as an experiment, there may be additional years of experimentation. Biologists and ecologists at GCMRC have worked in partnership with technical staff at WAPA in the design of the bug flows.

This collaboration has proved productive. To further the collaborative partnership, investigators in Project N will become part of this scientific exchange in order to identify hydrographs associated with the Bug Flows experiment that improve hydropower resource objectives, while meeting Bug Flows objectives, consistent with improvement and long-term sustainability of other downstream resources.

Trout Management Flow

As part of the LTEMP EIS (U.S. Department of Interior, 2016b), GCMRC scientists and GCDAMP stakeholders are currently discussing the design and implementation of a trout management flow (TMF) experiment to manage rainbow trout recruitment at Lees Ferry. Investigators in Project N will work with biologists and ecologists at GCMRC, and cooperators, who are developing proposed TMF experiments in order to determine how hydropower objectives can be met and improved through TMF experiments. Project N will focus on experiment specific hydrograph design to maintain or improve objectives specific to the hydropower resource goal defined in the LTEMP EIS.

High Flow Experiment

Investigators in Project N will assist the team of GCMRC sediment scientists in an effort to investigate the design parameters of high flow experiments (both annual and interannual considerations) to maintain or improve hydropower objectives. Project N will focus on experiment specific hydrograph designs to maintain or improve objectives specific to the hydropower resource goal defined in the LTEMP EIS. For example, modeling a change in ramp rates to maintain or improve the hydropower and recreational resource objectives is a possible application of Project N. For interannual modeling of sediment management and hydropower see Project J.1.

Hydropower Improvement Experiment

Investigators in Project N will identify experimental hydrographs at Glen Canyon Dam that improve the value or production of hydropower, outside of flow experiments specific to biological and physical resources, to better achieve the hydropower and energy resource goal. These experimental hydrographs to improve the value or production of hydropower will be consistent with the improvement and long-term sustainability of downstream resources.

Hydropower Metrics

Hydropower objectives to be considered in the investigation of the design of flow experiments will include, but not limited to, the following:

- Economic value of capacity ($/MW); and
- Economic value of energy ($/MWh).

Past research into changes in regional energy costs attributed to alteration of GCD operations have shown that no changes occur in hourly prices (U.S. Department of Interior, 2016b). Specifically, hourly energy prices at the regional hub important to GCD (Palo Verde) remain approximately the same with variation in production of energy at GCD. In addition, the analysis of experiments is a short-run analysis, assuming that demand for energy is inelastic (demand does not change with small changes in prices) and surplus power capacity exists. Therefore, changes in $/MW and $/MWh are accurate representations of the changes in consumer and producer surplus when evaluating minor, short-run changes in GCD operations. However, long-run changes in the energy sector may lead to a different economic outcome and a more complete modeling approach would be required. The evaluation of GCD operation and long-run changes in the electricity sector such as the integration of renewable energy, repurposing of federal hydropower resources, or power system capacity expansion would require a significant increase in research scope.

The aforementioned objectives are a function of operational parameters at Glen Canyon Dam (max ft^3/s, min ft^3/s, change in ft^3/s per hour or over 24 hours, etc.). These operational parameters and other assumptions are included in the development of optimization models (e.g., GTMax) used to maximize the economic value of hydropower (U.S. Department of Interior, 2016b). Examples of metrics to be reported as part of model output include:

- Electric generating capacity (MW);
- Electric generating energy (MWh);
- Min and max MWh within a week;
- Ramp rate (change in ft^3/s per hour); and
- Daily flow variation (change in ft^3/s over 24 hours).

As proposed, focusing on specific hydropower resource objectives (e.g., $/MW or $/MWh) facilitates a decision framework that supports the assessment of critical uncertainties and the prioritization of monitoring and research funding (Runge and others, 2015).

5.2. Outcomes and Products

Products from this project will be determined in coordination with Reclamation, WAPA, and other collaborators during Project N implementation and development. When applicable, presentations will be given at TWG and AMWG meetings, presentations at scientific meetings, and peer-reviewed scientific journal articles.

5.3. Personnel and Collaborations

Coordination will occur between scientists and technical staff from GCMRC and WAPA. In addition, support from other organizations, such as Argonne National Laboratory, may be sought depending on the specific scope of work. In support of coordination between scientists and technical staff from GCMRC and WAPA, all energy and power system models and data (e.g., GTMax, PLEXOS) in the analysis of experimental flows will be made available to investigators. GCMRC will be responsible for licensing fees associated with proprietary software whether coordinated with cooperators or acquired independently. These costs are captured in the Operating Expenses column of the Project N budget.

6. References

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7. Budget

Fiscal Year 2021								
Project N Hydropower Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							14.00%	
N.1. Hydropower monitoring and research	$15,863	$3,500	$4,500	$0	$0	$0	$3,341	**$27,204**
Total Project N	**$15,863**	**$3,500**	**$4,500**	**$0**	**$0**	**$0**	**$3,341**	**$27,204**

Fiscal Year 2022								
Project N Hydropower Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							22.00%	
N.1. Hydropower monitoring and research	$16,180	$1,500	$2,500	$0	$0	$0	$4,440	**$24,620**
Total Project N	**$16,180**	**$1,500**	**$2,500**	**$0**	**$0**	**$0**	**$4,440**	**$24,620**

Fiscal Year 2023								
Project N Hydropower Monitoring and Research	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							28.00%	
N.1. Hydropower monitoring and research	$16,504	$1,500	$2,500	$0	$0	$0	$5,741	**$26,245**
Total Project N	**$16,504**	**$1,500**	**$2,500**	**$0**	**$0**	**$0**	**$5,741**	**$26,245**

Appendix 1. Lake Powell Water Quality Monitoring

GCMRC has an existing five-year agreement with the Bureau of Reclamation (IA R13PG40028) to continue Lake Powell water quality monitoring through calendar year 2022. The statement of work will be included in the final draft of the work plan.

1.2. PROJECT TITLE

Historical Data Analysis, Water Quality Monitoring, and Drivers of Nutrient Availability in Lake Powell and Glen Canyon Dam Releases

1.3. BACKGROUND

The Lake Powell water quality monitoring program has been in existence since 1965 and represents a unique and valuable long-term record of water temperatures, dissolved oxygen concentrations, major ions and, more recently (beginning in 1990), nutrients and biological constituents. The monitoring program collects data on water-quality conditions at the forebay of the reservoir (2.4 km from the dam) on a monthly basis and at 25-30 sites reservoir-wide quarterly. Water temperature, specific conductance, dissolved oxygen, pH, redox potential, and turbidity are measured throughout the water column at each site with samples for major ionic constituents, nutrients, dissolved organic carbon, chlorophyll, phytoplankton and zooplankton being collected at selected sites. Physical and chemical information from this program was published as USGS Data Series Report DS-471 (last revised February 2015[1]) and biological data are contained in USGS Data Series Report DS-959 (last revised October 2015[2]). All information from this program is stored in the Water Quality Database (WQDB) in Microsoft Access, and a subset of the data (through 2013) is available for download with the DS-471 Data Series Report[1]. The Lake Powell long term monitoring program has undergone several assessments including a 1996 evaluation by GCMRC that highlighted the role of dam operations in controlling the quality of water in dam releases, a 2001 protocol evaluation panel that recommended a gradual shift in emphasis from Lake Powell to downstream, and a 2017 Water Quality Knowledge Assessment that describes the state of knowledge pertaining to water quality in Lake Powell dam release water. A follow-up protocol evaluation panel is being planned and will occur sometime in 2017.

Currently, downstream temperature monitoring has been moved to the GCMRC physical science program, and aquatic foodbase monitoring work has developed and conducts additional downstream monitoring of dissolved oxygen and other water quality parameters like turbidity and conductivity. Additionally, Reclamation has employed and maintained the cE-Qual-W2 reservoir model to provide projections of release temperature, dissolved oxygen, and other parameters[3].

There is renewed interest from Glen Canyon Dam Adaptive Management Program (GCDAMP) stakeholders in better understanding and describing the water quality in dam release water, particularly with respect to nutrient concentrations. This updated scope of work aims to outline the role of GCMRC in the ongoing Lake Powell monitoring program.

1. Description of Products or Services and Milestones

The objectives of this monitoring program have changed since 1965, reflecting changes in scientific interest as the reservoir filled, responsibilities of Reclamation for maintaining salinity levels in the Colorado River, and the monitoring status of Upper Colorado River basin reservoirs. Objectives have also been responsive to more recent environmental concerns related to the Grand Canyon Protection Act, the establishment of the GCDAMP, and the GCD Long-Term Experimental and Management Plan Environmental Impact Statement and subsequent Record of Decision.

Objectives of this long-term monitoring program include:

1. Determination of water-quality status and trends in Lake Powell and GCD releases.
2. Linking the historical record of Lake Powell water quality to various climatological and hydrological conditions.
3. Documentation of the effects of the structure and operation of GCD on the quality of water in Lake Powell and GCD releases.
4. Integration with GCDAMP information needs and downstream monitoring programs.
5. Documentation of the density structure and associated nutrient distribution in the water column at the GCD forebay and other locations in the reservoir to determine the quality of water available for release from GCD.
6. Assessment of the distribution and patterns of major ionic constituents in Lake Powell and GCD releases.
7. Assessment of the distribution and patterns of nutrient constituents in Lake Powell and GCD releases.
8. Assessment of the structure, status, and trends of the plankton community and its effect on primary and secondary production in Lake Powell.

Task 1. Details of Ongoing Monitoring Program (to be continued under this agreement)

The ongoing Lake Powell water-quality monitoring program consists of monthly surveys of the reservoir forebay and tailwater (conducted by GCMRC) and quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms of the reservoir to the inflow areas (conducted by Reclamation). The GCD forebay station is located approximately 2.4 km upstream from GCD.

Two tailwater sites are located immediately downstream from the dam and at Lees Ferry, approximately 25 km downstream. Depending on reservoir elevation, 21-37 established sites, including the forebay and tailwater stations, are sampled for the quarterly surveys.

At each site, initial surface observations (for example, bottom depth, Secchi depth, weather observations) are recorded, after which a depth profile of temperature, specific conductance, dissolved oxygen, pH, redox potential, turbidity, and chlorophyll florescence is collected, using the Seabird SBE19plusV2 instrument. These data are downloaded immediately after collection and viewed in the field to determine stratification patterns. Based on stratification patterns, chemical samples for major ionic constituents and nutrient concentrations are collected in the major strata at selected sites. Dissolved organic carbon samples are collected at the forebay tailwater, and tributary inflow sites. Biological samples for chlorophyll concentration, phytoplankton, and zooplankton are also collected at selected sites. Samples are filtered and preserved in the field for subsequent laboratory analysis.

Analysis for major ionic constituent, nutrient, and chlorophyll concentrations are performed by Reclamation's Lower Colorado Regional Laboratory in Boulder City, NV. Phytoplankton and zooplankton samples are analyzed under contract by BSA Environmental, Inc. Data processing of the Seabird profile data is performed in the office shortly after the field survey. All field and analytical data are entered into the WQDB database for statistical and graphical analysis and long-term storage.

Details of the monitoring program, a description of the WQDB database, and physicochemical data from 1965-2013 are available as a USGS Data Series report[1] at https://pubs.usgs.gov/ds/471/.

Task 2. Historical Data Analysis – Towards Improved Predictive Capacity for Reservoir Nutrient Dynamics

Given the large volume of historical nutrient data available for Lake Powell, the river outlet works, and Lees Ferry, and given that there has been relatively little analysis of the nutrient data, GCMRC will spend time assessing spatial and temporal trends in nutrient concentrations and potential environmental drivers of nutrient availability. The historical data from this monitoring program has already been used for a number of important purposes including the development of a working CE-QUAL2 model and the description of long term trends in stratification and associated oxygen dynamics. Still, there is a great deal of additional analysis that can be done to better elucidate the controls on reservoir and outlet chemistry. Work by Wildman and Hering suggests that deltaic sediments in the inlets of Lake Powell may be a dominant source of phosphorus to the reservoir (via re-mobilization during flooding events)[4]. Still, there is also substantial variation in inflow concentrations of nutrients that may also control in-reservoir availability. Finally, recent work done in other systems (streams and lakes) has shown the important role that calcium carbonate formation can play in sequestering phosphorus from the water column. To understand the fate of nutrient loading to Lake Powell's inlets, the USGS program LOADEST will be used in combination with historic discharge and nutrient concentrations (records generally exist from 1990-2000) from the NWIS stations: Green River at Green River, Colorado River near Cisco Utah, and San Juan River at Bluff. Modeled riverine nutrient loading for this decade will be compared to nutrient measurements in the Lake Powell dataset to look for an advective signal of riverine nutrient loading. We will also use the long term dataset to look for relationships between phosphorus concentrations and factors that control, or are influenced by, calcium carbonate deposition: chlorophyll a, pH, [Ca^{2+}], conductivity, alkalinity, turbidity, and secchi depth. Together, these data sources will help us better identify the most important processes controlling P availability in Lake Powell and Glen Canyon Dam releases and will also inform the development of future sampling and experimental plans.

Task 3. Revisions to Existing Program

Given recent evidence that the nutrient content of Lake Powell's outflow is an important driver of biological processes in downstream ecosystems[5,6], the ongoing monitoring at the Wahweap station will be expanded to better capture nutrient dynamics along a vertical profile. Currently, nutrient samples are collected at the Wahweap station monthly from the surface, bottom, and from the depth of the penstock. The necessary degree of increased resolution will be decided based on preliminary sampling at very high resolution (15+ depths) during thermally stratified conditions when nutrient content is expected to vary the most by depth. Based on the initial highly resolved sampling, depths will be chosen that adequately represent transitions between density layers while avoiding re-sampling within regions of homogenous nutrient concentration. Depths will be matched with the forebay thermistor string maintained by Reclamation such that temperature can be used as a tracer of vertical mixing. To best support this approach, we will also deploy a string of conductivity sensors near the thermistor string to better characterize density mixing. Nutrient samples will also be collected from within the interflow at each inlet site during the quarterly sampling (Escalante, San Juan, and Colorado). The interflow will be identified by looking at the Seabird conductivity, turbidity, and temperature profiles and this sampling will help us determine to what extent excess P may be getting mobilized off of sediment deltas during higher inflow events. Depending on the results of this sampling and the historical data analysis, additional targeted sampling may be conducted in the reservoir inlets to better ascertain the controls on nutrient transformation and transport.

In addition to expanded sampling at Wahweap and inlet sites, historical data will be thoroughly assessed to look for redundancies in sample effort. For example, a thorough comparison of measurements being made at Wahweap, within the draft tubes, and at Lees Ferry will be conducted in order to assess the necessity of maintaining each of these sites. Methodology for chlorophyll sample collection will also be examined systematically so as to properly assess differences between methods and annotate the WQDB accordingly. Samples were previously preserved via desiccation, but are now chilled or frozen.

Task 4. Characterizing Nutrient Dynamics During Experimental Flows

The potential for experimental flows to modify downstream nutrient regimes will be examined by conducting targeted nutrient sampling before, during, and after experimental flows. Previous sampling efforts have documented the capacity for changes in flow at GCD outlets to affect the chemistry of water below the dam. For example, work by Hueftle and Stevens showed that the 1996 spring high flow event diminished bottom water hypoxia in Lake Powell as far as 100 km uplake while also resulting in high salinity, high oxygen concentrations, and damped DO and pH fluctuations in the dam tailwater [7]. Nutrient data collected 4 days before and 2 days after the high flow event showed drops in phosphorus concentration at both the penstock and river outlet works, although the magnitude of this drop is difficult to determine given the detection limit of the analyses used at that time. Monitoring during the 2008 high flow experiment also showed elevated dissolved oxygen concentrations downstream of the dam (at maximum 120% of saturation), but relatively minimal effects on the structure of the water column upstream of the dam[8]. Still, this study only considered water temperature, specific conductance, and dissolved oxygen, not nutrients. Targeted profiling at Wahweap and grab sampling at Lees Ferry will be conducted at least twice prior to experimental flow, twice during experimental flow, and twice post experimental flow to better quantify the effects of flow regime on reservoir and outlet chemistry. Thermistor string data will also be examined for changes in physical stratification as well as nutrient dynamics.

Task 5. Improving Access to Historical Dataset

Given the relatively unique and valuable nature of the historic Lake Powell water quality database, GCMRC will identify an appropriate, easily visible online location for the dataset to facilitate public access and download. GCMRC currently maintains the Lake Powell water quality database in-house in a Microsoft Access™ format. A static download of data through 2013 is available in association with Data Series Report DS-471[1]; however a currently-updated version of the database is not available for download on the GCMRC website. After quality control-checking the current WQDB, the data will be made available online via ScienceBase and other options for making the data publicly accessible will be considered by the requesting agency, the servicing agency, and interested stakeholders and cooperators. Options include: a link to the Access database on the GCMRC website that is periodically updated, importing the data to NWIS, or adding the data to a new Water Quality Portal that serves to aggregate data from across government agencies (e.g. the U.S. Environmental Protection Agency, the U.S. Geological Survey, and the National Water Quality Monitoring Council) resulting in a current 297 million water quality records from more than 2.7 million distinct sites (https://www.waterqualitydata.us/).

2. References

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5. Yackulic, C.B., 2017, It's not just about temperature and flow—The potential role of nutrients as a driver of Colorado River ecosystem dynamics—presentation: GCDAMP Annual Reporting Meeting.
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3. Budget

Fiscal Year 2021								
Appendix 1 Lake Powell Fund	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							14.00%	
Lake Powell Water Quality Monitoring	$138,950	$9,109	$11,619	$0	$0	$0	$55,887	**$215,565**
Total Lake Powell Fund	**$138,950**	**$9,109**	**$11,619**	**$0**	**$0**	**$0**	**$55,887**	**$215,565**

Fiscal Year 2022								
Appendix 1 Lake Powell Fund	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.00%	
Lake Powell Water Quality Monitoring	$141,729	$8,814	$11,968	$0	$0	$0	$56,879	**$219,389**
Total Lake Powell Fund	**$141,729**	**$8,814**	**$11,968**	**$0**	**$0**	**$0**	**$56,879**	**$219,389**

Fiscal Year 2023								
Appendix 1 Lake Powell Fund	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							28.00%	
Lake Powell Water Quality Monitoring (*current agreement expires*)	$0	$0	$0	$0	$0	$0	$0	**$0**
Total Lake Powell Fund	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

Appendix 2: Experimental Fund Summaries by Year

Fiscal Year 2021									
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
	Experimental Fund Budget							14.00%	
A	**LTEMP HFE Experimental Projects**								
A.4	HFE Experimental Fund	$31,617	$1,000	$25,000	$18,800	$0	$0	$10,698	**$87,116**
	Total A	**$31,617**	**$1,000**	**$25,000**	**$18,800**	**$0**	**$0**	**$10,698**	**$87,116**
B	**LTEMP HFE Experimental Projects**								
B.6.1	Extended duration HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$12,815	$1,200	$1,000	$80,203	$70,749	$0	$15,453	**$181,420**
B.6.2	Proactive HFE (1 set of sandbar surveys w/o bathymetry)	$12,815	$1,200	$1,000	$36,449	$44,253	$0	$8,533	**$104,250**
B.6.3	Proactive HFE (1 set of sandbar surveys with bathymetry)	$15,378	$1,200	$1,000	$62,609	$62,586	$0	$13,104	**$155,877**
B.6.4	Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$12,815	$1,200	$1,000	$72,898	$66,380	$0	$14,299	**$168,592**
B.6.5	Western Grand Canyon (5 surveys around fall HFE)	$6,835	$4,800	$3,000	$29,687	$55,309	$0	$7,864	**$107,495**
	Total B	**$60,659**	**$9,600**	**$7,000**	**$281,845**	**$299,277**	**$0**	**$59,253**	**$717,634**
E	**Spring Powerplant Capacity Flow Experiments**								
E.4	Mapping Vegetation Response to Experimental Flows	$1,709	$500	$9,000	$12,000	$20,000	$0	$3,849	**$47,058**
	Total E	**$1,709**	**$500**	**$9,000**	**$12,000**	**$20,000**	**$0**	**$3,849**	**$47,058**
F	**Spring Powerplant Capacity Flow Experiments**								
F.5	Foodbase Response to Spring Powerplant Capacity Flows	$42,854	$13,000	$1,000	$5,000	$0	$12,000	$8,660	**$82,514**
	Total F	**$42,854**	**$13,000**	**$1,000**	**$5,000**	**$0**	**$12,000**	**$8,660**	**$82,514**
J	**LTEMP Flow Experiments**								
J.3	Recreation Monitoring and Research	$0	$0	$0	$0	$10,000	$0	$300	**$10,300**
	Total J	**$0**	**$0**	**$0**	**$0**	**$10,000**	**$0**	**$300**	**$10,300**
	Total Experimental Fund (FY21)	**$136,839**	**$24,100**	**$42,000**	**$317,645**	**$329,277**	**$12,000**	**$82,760**	**$944,621**

Fiscal Year 2022									
Project	**Project Description**	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
	Experimental Fund Budget							22.00%	
A	**LTEMP HFE Experimental Projects**								
A.4	HFE Experimental Fund	$32,249	$1,000	$25,000	$19,400	$0	$0	$17,083	**$94,732**
	Total A	**$32,249**	**$1,000**	**$25,000**	**$19,400**	**$0**	**$0**	**$17,083**	**$94,732**
B	**LTEMP HFE Experimental Projects**								
B.6.1	Extended duration HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$13,072	$1,200	$1,000	$81,646	$70,749	$0	$23,444	**$191,111**
B.6.2	Proactive HFE (1 set of sandbar surveys w/o bathymetry)	$13,072	$1,200	$1,000	$37,105	$44,253	$0	$12,850	**$109,480**
B.6.3	Proactive HFE (1 set of sandbar surveys with bathymetry)	$15,686	$1,200	$1,000	$63,736	$62,586	$0	$19,834	**$164,042**
B.6.4	Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$13,072	$1,200	$1,000	$74,210	$66,380	$0	$21,677	**$177,539**
B.6.5	Western Grand Canyon (5 surveys around fall HFE)	$6,972	$4,800	$3,000	$30,221	$55,309	$0	$11,558	**$111,859**
	Total B	**$61,872**	**$9,600**	**$7,000**	**$286,918**	**$299,277**	**$0**	**$89,364**	**$754,031**
E	**Spring Powerplant Capacity Flow Experiments**								
E.4	Mapping Vegetation Response to Experimental Flows	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total E	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
F	**Spring Powerplant Capacity Flow Experiments**								
F.5	Foodbase Response to Spring Powerplant Capacity Flows	$107,616	$0	$0	$0	$0	$12,000	$23,675	**$143,291**
	Total F	**$107,616**	**$0**	**$0**	**$0**	**$0**	**$12,000**	**$23,675**	**$143,291**
J	**LTEMP Flow Experiments**								
J.3	Recreation Monitoring and Research	$0	$0	$0	$0	$10,000	$0	$300	**$10,300**
	Total J	**$0**	**$0**	**$0**	**$0**	**$10,000**	**$0**	**$300**	**$10,300**
	Total Experimental Fund (FY22)	**$201,737**	**$10,600**	**$32,000**	**$306,318**	**$309,277**	**$12,000**	**$130,422**	**$1,002,355**

Fiscal Year 2023									
Project	**Project Description**	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
	Experimental Fund Budget							28.00%	
A	**LTEMP HFE Experimental Projects**								
A.4	HFE Experimental Fund	$32,894	$1,000	$25,000	$19,900	$0	$0	$22,062	**$100,857**
	Total A	**$32,894**	**$1,000**	**$25,000**	**$19,900**	**$0**	**$0**	**$22,062**	**$100,857**
B	**LTEMP HFE Experimental Projects**								
B.6.1	Extended duration HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$13,333	$1,200	$1,000	$83,116	$70,749	$0	$29,744	**$199,142**
B.6.2	Proactive HFE (1 set of sandbar surveys w/o bathymetry)	$13,333	$1,200	$1,000	$37,773	$44,253	$0	$16,253	**$113,812**
B.6.3	Proactive HFE (1 set of sandbar surveys with bathymetry)	$16,000	$1,200	$1,000	$64,883	$62,586	$0	$25,141	**$170,810**
B.6.4	Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$13,333	$1,200	$1,000	$75,545	$66,380	$0	$27,493	**$184,952**
B.6.5	Western Grand Canyon (5 surveys around fall HFE)	$7,111	$4,800	$3,000	$30,765	$55,309	$0	$14,449	**$115,434**
	Total B	**$63,110**	**$9,600**	**$7,000**	**$292,083**	**$299,277**	**$0**	**$113,080**	**$784,149**
E	**Spring Powerplant Capacity Flow Experiments**								
E.4	Mapping Vegetation Response to Experimental Flows	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total E	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
F	**Spring Powerplant Capacity Flow Experiments**								
F.5	Foodbase Response to Spring Powerplant Capacity Flows	$32,758	$0	$0	$0	$0	$12,000	$9,172	**$53,931**
	Total F	**$32,758**	**$0**	**$0**	**$0**	**$0**	**$12,000**	**$9,172**	**$53,931**
J	**LTEMP Flow Experiments**								
J.3	Recreation Monitoring and Research	$0	$0	$0	$0	$10,000	$0	$300	**$10,300**
	Total J	**$0**	**$0**	**$0**	**$0**	**$10,000**	**$0**	**$300**	**$10,300**
	Total Experimental Fund (FY23)	**$128,762**	**$10,600**	**$32,000**	**$311,983**	**$309,277**	**$12,000**	**$144,615**	**$949,237**

Appendix 3. Potential Budget Allocation Summary by Project and Year

Project	FY2021	FY2022	FY2023
Project A. Streamflow, Water Quality, and Sediment Transport	$ 1,207,959	$ 1,126,263	$ 1,187,762
Project B. Sandbar and Sediment Storage Monitoring and Research	$ 1,023,311	$ 906,981	$ 994,345
Project C. Riparian Vegetation Monitoring and Research	$ 325,492	$ 332,540	$ 341,402
Project D. Effects of Dam Operations and Vegetation Management for Archaeological Sites	$ 324,413	$ 314,129	$ 319,935
Project E. Nutrients, Flow, and Temperature as Ecosystem Drivers	$ 408,095	$ 293,861	$ 287,270
Project F. Aquatic Invertebrate Ecology	$ 766,480	$ 709,409	$ 699,786
Project G. Humpback Chub Monitoring and Research	$ 1,661,134	$ 1,834,756	$ 1,597,633
Project H. Salmonid Monitoring and Research	$ 747,966	$ 511,410	$ 498,356
Project I. Warm-water Native and Nonnative Fish Monitoring and Research	$ 552,542	$ 671,368	$ 658,125
Project J. Socioeconomic Research	$ 208,345	$ 204,352	$ 192,953
Project K. Geospatial Science, Data Management, and Technology	$ 424,407	$ 464,284	$ 511,345
Project L. Overflight Remote Sensing	$ 897,350	$ 283,876	$ 315,509
Project M. Leadership, Management, and Support	$ 1,406,428	$ 1,427,412	$ 1,491,839
Project N. Hydropower Monitoring and Research	$ 27,204	$ 24,620	$ 26,245
Total Cost	$ 9,981,127	$ 9,105,262	$ 9,122,504
Anticipated AMP Funding Available (80.0% and 0% CPI)	$ 9,088,000	$ 9,088,000	$ 9,088,000
Overflight Carryover: FY18-20 savings + logistics funding from 2020 cancelled trips	$ 445,000	$ -	$ -
Anticipated Carryover Funding Available	$ 500,000	$ 51,873	$ 34,611
Long/Short	**$51,873**	**$34,611**	**$107**
Appendix 1: Lake Powell Water Quality Monitoring **NOT GCDAMP Funded**	$ 215,565	$ 219,389	N/A
Appendix 2: Experimental Fund Proposals	$ 944,621	$ 1,002,355	$ 949,237

Appendix 3a. Potential Budget Allocation – FY2021

Fiscal Year 2021									
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
								14.00%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$141,130	$4,200	$13,000	$20,700	$0	$96,377	$25,064	**$300,471**
A.2	Continuous water quality parameters	$160,968	$800	$11,000	$20,700	$0	$28,260	$27,085	**$248,813**
A.3	Sediment transport and budgeting	$284,019	$5,000	$42,400	$20,700	$0	$257,260	$49,297	**$658,675**
	Total A	**$586,116**	**$10,000**	**$66,400**	**$62,100**	**$0**	**$381,897**	**$101,446**	**$1,207,960**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar monitoring	$141,848	$2,000	$2,000	$25,426	$188,829	$0	$29,643	**$389,746**
B.2	Sediment storage monitoring and research	$156,829	$1,000	$32,200	$109,362	$175,331	$0	$47,175	**$521,897**
B.3	Control network and survey support	$81,954	$1,000	$15,000	$0	$0	$0	$13,714	**$111,668**
	Total B	**$380,631**	**$4,000**	**$49,200**	**$134,788**	**$364,160**	**$0**	**$90,532**	**$1,023,311**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$65,898	$3,590	$1,650	$60,881	$8,500	$0	$18,738	**$159,256**
C.2	Plant experiments	$6,856	$0	$0	$0	$11,800	$0	$1,314	**$19,970**
C.3	Modeling riparian vegetation	$34,280	$0	$0	$0	$92,347	$0	$7,570	**$134,197**
C.4	Vegetation management support	$6,856	$0	$0	$0	$4,130	$0	$1,084	**$12,070**
	Total C	**$113,890**	**$3,590**	**$1,650**	**$60,881**	**$116,777**	**$0**	**$28,705**	**$325,492**
D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Dam operation and vegetation management effects for archaeological sites	$193,851	$6,400	$7,000	$18,850	$0	$0	$31,654	**$257,755**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$28,707	$5,000	$500	$0	$0	$0	$4,789	**$38,996**
D.3	Cultural program administrative history	$22,966	$1,000	$300	$0	$0	$0	$3,397	**$27,663**
	Total D	**$245,523**	**$12,400**	**$7,800**	**$18,850**	**$0**	**$0**	**$39,840**	**$324,413**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$67,797	$1,000	$5,000	$0	$81,500	$0	$12,777	**$168,074**
E.2	Rates and composition of primary producers in the Colorado River	$123,490	$7,400	$13,000	$6,400	$0	$0	$21,041	**$171,331**
E.3	Productivity at higher trophic levels (fish metabolism) - secondary production	$44,755	$0	$15,500	$0	$0	$0	$8,436	**$68,691**
	Total E	**$236,042**	**$8,400**	**$33,500**	**$6,400**	**$81,500**	**$0**	**$42,253**	**$408,095**
F	**Aquatic Invertebrate Ecology**								
F.1	Aquatic invertebrate monitoring in Marble and Grand Canyons	$257,778	$3,000	$28,000	$16,386	$0	$0	$42,723	**$347,888**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$202,842	$12,503	$8,000	$7,500	$0	$0	$32,318	**$263,164**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$79,833	$5,702	$1,000	$0	$0	$0	$12,115	**$98,649**
F.4	Diets of native and nonnative Colorado River fishes	$48,807	$0	$1,000	$0	$0	$0	$6,973	**$56,780**
	Total F	**$589,260**	**$21,205**	**$38,000**	**$23,886**	**$0**	**$0**	**$94,129**	**$766,480**

G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$103,619	$4,000	$7,000	$0	$0	$0	$16,047	**$130,666**
G.2	Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$12,640	$0	$14,200	$96,789	$342,506	$0	$27,583	**$493,718**
G.3	Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$113,365	$0	$13,000	$224,982	$0	$0	$49,189	**$400,536**
G.4	Remote PIT tag array monitoring in the LCR	$22,482	$0	$6,000	$7,032	$0	$0	$4,972	**$40,487**
G.5	Monitoring HBC aggregation relative abundance & distribution	$10,060	$0	$14,100	$55,220	$96,240	$0	$14,000	**$189,621**
G.6	Juvenile chub monitoring - Western Canyon	$68,450	$0	$17,600	$186,387	$0	$0	$38,141	**$310,578**
G.7	Chute Falls translocations	$4,962	$0	$2,600	$15,230	$67,520	$0	$5,216	**$95,528**
	Total G	**$335,579**	**$4,000**	**$74,500**	**$585,640**	**$506,266**	**$0**	**$155,149**	**$1,661,134**
H	**Salmonid Research and Monitoring Project**								
H.1	Rainbow trout monitoring in Glen Canyon (AGFD)	$9,924	$0	$2,000	$14,111	$88,000	$0	$6,285	**$120,320**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$83,130	$500	$42,816	$182,750	$37,000	$0	$44,397	**$390,594**
H.3	Brown Trout Early Life Stage Survey (BTELSS)	$33,285	$12,950	$100	$37,303	$0	$0	$11,709	**$95,347**
H.4	Salmonid modeling	$49,312	$0	$0	$0	$83,000	$0	$9,394	**$141,705**
	Total H	**$175,651**	**$13,450**	**$44,916**	**$234,164**	**$208,000**	**$0**	**$71,785**	**$747,966**
I	**Warm-water Native and Non-Native Fish Monitoring and Research**								
I.1	System-wide native fish & invasive aquatic species monitoring (AGFD)	$12,640	$0	$11,920	$46,571	$217,550	$0	$16,485	**$305,166**
I.2	Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$70,601	$1,500	$3,000	$7,029	$21,000	$0	$12,128	**$115,258**
I.3	Impacts of channel catfish in the LCR	$104,693	$1,500	$6,600	$3,100	$0	$0	$16,225	**$132,118**
	Total I	**$187,934**	**$3,000**	**$21,520**	**$56,700**	**$238,550**	**$0**	**$44,838**	**$552,542**
J	**Socioeconomic Research**								
J.1	Predictive models for adaptive management	$48,118	$1,500	$250	$0	$10,500	$0	$7,297	**$67,664**
J.2	Brown trout incentivized harvest	$74,028	$2,500	$1,250	$0	$50,500	$0	$12,404	**$140,681**
	Total J	**$122,145**	**$4,000**	**$1,500**	**$0**	**$61,000**	**$0**	**$19,700**	**$208,346**
K	**Geospatial Science, Data Management and Technology Project**								
K.1	Geospatial science	$147,535	$2,303	$2,400	$0	$0	$0	$21,313	**$173,552**
K.2	Database management	$122,806	$2,303	$700	$0	$0	$0	$17,613	**$143,423**
K.3	Remote monitoring and advanced technology	$90,739	$500	$3,000	$0	$0	$0	$13,193	**$107,433**
	Total K	**$361,081**	**$5,107**	**$6,100**	**$0**	**$0**	**$0**	**$52,120**	**$424,408**
L	**Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP**								
L.1	Overflight remote sensing	$166,837	$3,000	$511,000	$33,493	$80,596	$0	$102,424	**$897,350**
	Total L	**$166,837**	**$3,000**	**$511,000**	**$33,493**	**$80,596**	**$0**	**$102,424**	**$897,350**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$716,852	$30,000	$121,700	$0	$0	$0	$121,597	**$990,149**
M.2	Logistics staff	$264,218	$7,000	$0	$0	$11,000	$0	$38,301	**$320,519**
M.3	IT	$0	$0	$84,000	$0	$0	$0	$11,760	**$95,760**
	Total M	**$981,070**	**$37,000**	**$205,700**	**$0**	**$11,000**	**$0**	**$171,658**	**$1,406,427**

N	**Hydropower Monitoring and Research**								
N.1	Hydropower monitoring and research	$15,863	$3,500	$4,500	$0	$0	$0	$3,341	**$27,204**
	Total N	**$15,863**	**$3,500**	**$4,500**	**$0**	**$0**	**$0**	**$3,341**	**$27,204**
	Total (FY21)	**$4,497,622**	**$132,652**	**$1,066,286**	**$1,216,902**	**$1,667,848**	**$381,897**	**$1,017,920**	**$9,981,127**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$9,088,000**
	AMP Over/Under Budget								**($893,127)**
	Overflight Carryover: FY18-20 savings + logistics funding from 2020 cancelled trips								$445,000
	Anticipated Carryover Funding Available								$500,000
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								$51,873
	Lake Powell								
	Lake Powell	$138,950	$9,109	$11,619	$0	$0	$0	$55,887	**$215,565**
	GCMRC Grand Total (w/ Lake Powell)	**$4,636,571**	**$141,761**	**$1,077,905**	**$1,216,902**	**$1,667,848**	**$381,897**	**$1,073,807**	**$10,196,693**

Appendix 3a. Potential Budget Allocation – FY2022

				Fiscal Year 2022					
Project	**Project Description**	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
								22.00%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$143,952	$4,200	$7,000	$21,300	$0	$98,267	$38,819	**$313,539**
A.2	Continuous water quality parameters	$52,256	$800	$11,000	$21,300	$0	$23,260	$18,778	**$127,394**
A.3	Sediment transport and budgeting	$289,699	$5,000	$37,500	$21,300	$0	$254,060	$77,770	**$685,329**
	Total A	**$485,907**	**$10,000**	**$55,500**	**$63,900**	**$0**	**$375,587**	**$135,368**	**$1,126,262**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar monitoring	$163,436	$2,000	$11,000	$26,011	$208,796	$0	$50,802	**$462,045**
B.2	Sediment storage monitoring and research	$160,236	$2,000	$6,000	$0	$144,497	$0	$41,347	**$354,080**
B.3	Control network and survey support	$58,472	$1,000	$15,000	$0	$0	$0	$16,384	**$90,856**
	Total B	**$382,144**	**$5,000**	**$32,000**	**$26,011**	**$353,293**	**$0**	**$108,533**	**$906,981**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$75,625	$3,940	$1,565	$42,141	$8,500	$0	$27,375	**$159,146**
C.2	Plant experiments	$8,383	$0	$0	$0	$2,360	$0	$1,915	**$12,658**
C.3	Modeling riparian vegetation	$41,916	$0	$0	$0	$92,347	$0	$11,992	**$146,254**
C.4	Vegetation management support	$8,383	$0	$0	$0	$4,130	$0	$1,968	**$14,481**
	Total C	**$134,307**	**$3,940**	**$1,565**	**$42,141**	**$107,337**	**$0**	**$43,250**	**$332,540**
D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Dam operation and vegetation management effects for archaeological sites	$184,803	$500	$150	$19,174	$0	$0	$45,018	**$249,645**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$29,281	$150	$0	$0	$0	$0	$6,475	**$35,906**
D.3	Cultural program administrative history	$23,425	$0	$0	$0	$0	$0	$5,153	**$28,578**
	Total D	**$237,509**	**$650**	**$150**	**$19,174**	**$0**	**$0**	**$56,646**	**$314,129**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$60,424	$1,000	$3,922	$0	$14,500	$0	$14,811	**$94,657**
E.2	Rates and composition of primary producers in the Colorado River	$89,758	$9,500	$10,000	$0	$0	$0	$24,037	**$133,294**
E.3	Productivity at higher trophic levels (fish metabolism) - secondary production	$54,025	$0	$0	$0	$0	$0	$11,886	**$65,911**
	Total E	**$204,206**	**$10,500**	**$13,922**	**$0**	**$14,500**	**$0**	**$50,733**	**$293,862**
F	**Aquatic Invertebrate Ecology**								
F.1	Aquatic invertebrate monitoring in Marble and Grand Canyons	$243,160	$3,390	$28,540	$16,964	$0	$0	$64,252	**$356,306**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$193,171	$12,869	$8,240	$7,500	$0	$0	$48,792	**$270,572**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$0	$0	$0	$0	$0	$0	$0	**$0**
F.4	Diets of native and nonnative Colorado River fishes	$65,225	$1,393	$1,030	$0	$0	$0	$14,883	**$82,531**
	Total F	**$501,556**	**$17,653**	**$37,810**	**$24,464**	**$0**	**$0**	**$127,926**	**$709,409**

G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$112,117	$4,000	$2,000	$0	$0	$0	$25,986	**$144,102**
G.2	Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$20,245	$0	$14,200	$105,120	$342,506	$0	$40,980	**$523,051**
G.3	Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$112,285	$0	$13,000	$231,043	$0	$0	$78,392	**$434,720**
G.4	Remote PIT tag array monitoring in the LCR	$32,193	$0	$6,000	$8,375	$0	$0	$10,245	**$56,812**
G.5	Monitoring HBC aggregation relative abundance & distribution	$8,763	$0	$24,100	$84,774	$110,740	$0	$29,202	**$257,579**
G.6	Juvenile chub monitoring - Western Canyon	$52,788	$0	$17,600	$191,056	$0	$0	$57,518	**$318,962**
G.7	Chute Falls translocations	$5,061	$0	$2,600	$16,915	$67,520	$0	$7,432	**$99,529**
	Total G	**$343,451**	**$4,000**	**$79,500**	**$637,284**	**$520,766**	**$0**	**$249,755**	**$1,834,756**
H	**Salmonid Research and Monitoring Project**								
H.1	Rainbow trout monitoring in Glen Canyon (AGFD)	$10,123	$0	$1,300	$14,200	$88,000	$0	$8,277	**$121,900**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$91,408	$5,000	$17,272	$84,805	$17,000	$0	$44,177	**$259,662**
H.3	Brown Trout Early Life Stage Survey (BTELSS)	$30,368	$0	$0	$0	$0	$0	$6,681	**$37,049**
H.4	Salmonid modeling	$39,762	$0	$0	$0	$43,000	$0	$10,038	**$92,799**
	Total H	**$171,661**	**$5,000**	**$18,572**	**$99,005**	**$148,000**	**$0**	**$69,172**	**$511,410**
I	**Warm-water Native and Non-Native Fish Monitoring and Research**								
I.1	System-wide native fish & invasive aquatic species monitoring (AGFD)	$10,123	$0	$10,000	$47,279	$217,550	$0	$21,355	**$306,307**
I.2	Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$86,590	$0	$500	$23,356	$55,560	$0	$25,965	**$191,970**
I.3	Impacts of channel catfish in the LCR	$137,078	$0	$1,600	$3,200	$0	$0	$31,213	**$173,091**
	Total I	**$233,790**	**$0**	**$12,100**	**$73,835**	**$273,110**	**$0**	**$78,533**	**$671,368**
J	**Socioeconomic Research**								
J.1	Predictive models for adaptive management	$49,080	$1,500	$250	$0	$0	$0	$11,183	**$62,013**
J.2	Brown trout incentivized harvest	$75,508	$1,500	$1,250	$0	$45,500	$0	$18,582	**$142,340**
	Total J	**$124,588**	**$3,000**	**$1,500**	**$0**	**$45,500**	**$0**	**$29,764**	**$204,353**
K	**Geospatial Science, Data Management and Technology Project**								
K.1	Geospatial science	$191,141	$2,470	$1,400	$0	$0	$0	$42,903	**$237,914**
K.2	Database management	$144,724	$2,470	$700	$0	$0	$0	$32,537	**$180,431**
K.3	Remote monitoring and advanced technology	$35,106	$500	$2,050	$0	$0	$0	$8,284	**$45,940**
	Total K	**$370,971**	**$5,440**	**$4,150**	**$0**	**$0**	**$0**	**$83,723**	**$464,284**
L	**Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP**								
L.1	Overflight remote sensing	$164,641	$0	$0	$0	$80,596	$0	$38,639	**$283,876**
	Total L	**$164,641**	**$0**	**$0**	**$0**	**$80,596**	**$0**	**$38,639**	**$283,876**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$690,221	$20,000	$108,000	$0	$0	$0	$180,009	**$998,229**
M.2	Logistics staff	$269,502	$3,000	$0	$0	$11,000	$0	$60,281	**$343,783**
M.3	IT	$0	$0	$70,000	$0	$0	$0	$15,400	**$85,400**
	Total M	**$959,723**	**$23,000**	**$178,000**	**$0**	**$11,000**	**$0**	**$255,689**	**$1,427,412**

N	**Hydropower Monitoring and Research**								
N.1	Hydropower monitoring and research	$16,180	$1,500	$2,500	$0	$0	$0	$4,440	**$24,620**
	Total N	**$16,180**	**$1,500**	**$2,500**	**$0**	**$0**	**$0**	**$4,440**	**$24,620**
	Total (FY22)	**$4,330,636**	**$89,683**	**$437,269**	**$985,813**	**$1,554,101**	**$375,587**	**$1,332,171**	**$9,105,262**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$9,088,000**
	AMP Over/Under Budget								**-$17,262**
	Overflight Carryover: FY18-20 savings + logistics funding from 2021 cancelled trips								$0
	Anticipated Carryover Funding Available								$51,873
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								$34,611
	Lake Powell								
	Lake Powell	$141,729	$8,814	$11,968	$0	$0	$0	$56,879	**$219,389**
	GCMRC Grand Total (w/ Lake Powell)	**$4,472,365**	**$98,497**	**$449,237**	**$985,813**	**$1,554,101**	**$375,587**	**$1,389,050**	**$9,324,651**

Appendix 3a. Potential Budget Allocation – FY2023

Fiscal Year 2023									
Project	**Project Description**	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
								28.00%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$146,831	$4,200	$8,000	$22,000	$0	$100,157	$50,689	**$331,877**
A.2	Continuous water quality parameters	$56,704	$800	$11,000	$22,000	$0	$23,260	$25,341	**$139,106**
A.3	Sediment transport and budgeting	$295,493	$5,000	$37,600	$22,000	$0	$255,860	$100,826	**$716,779**
	Total A	**$499,029**	**$10,000**	**$56,600**	**$66,000**	**$0**	**$379,277**	**$176,856**	**$1,187,762**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar monitoring	$165,218	$1,750	$10,000	$33,622	$191,942	$0	$64,724	**$467,256**
B.2	Sediment storage monitoring and research	$166,996	$1,750	$5,200	$0	$201,570	$0	$54,752	**$430,268**
B.3	Control network and survey support	$59,642	$1,000	$15,000	$0	$0	$0	$21,180	**$96,821**
	Total B	**$391,856**	**$4,500**	**$30,200**	**$33,622**	**$393,512**	**$0**	**$140,655**	**$994,345**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$76,710	$3,240	$3,310	$42,930	$8,500	$0	$35,588	**$170,278**
C.2	Plant experiments	$8,551	$0	$0	$0	$1,180	$0	$2,430	**$12,160**
C.3	Modeling riparian vegetation	$42,754	$0	$0	$0	$86,447	$0	$14,565	**$143,765**
C.4	Vegetation management support	$8,551	$0	$0	$0	$4,130	$0	$2,518	**$15,199**
	Total C	**$136,566**	**$3,240**	**$3,310**	**$42,930**	**$100,257**	**$0**	**$55,100**	**$341,403**
D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Dam operation and vegetation management effects for archaeological sites	$186,879	$600	$850	$19,507	$0	$0	$58,194	**$266,030**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$41,813	$250	$50	$0	$0	$0	$11,792	**$53,905**
D.3	Cultural program administrative history	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total D	**$228,692**	**$850**	**$900**	**$19,507**	**$0**	**$0**	**$69,986**	**$319,935**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$70,536	$1,000	$3,500	$0	$0	$0	$21,010	**$96,046**
E.2	Rates and composition of primary producers in the Colorado River	$59,436	$7,000	$9,865	$0	$0	$0	$21,364	**$97,665**
E.3	Productivity at higher trophic levels (fish metabolism) - secondary production	$70,077	$2,500	$516	$0	$0	$0	$20,466	**$93,559**
	Total E	**$200,049**	**$10,500**	**$13,881**	**$0**	**$0**	**$0**	**$62,840**	**$287,270**
F	**Aquatic Invertebrate Ecology**								
F.1	Aquatic invertebrate monitoring in Marble and Grand Canyons	$235,165	$3,792	$29,096	$17,542	$0	$0	$79,967	**$365,562**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$185,876	$13,247	$8,487	$7,500	$0	$0	$60,231	**$275,341**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$0	$0	$0	$0	$0	$0	$0	**$0**
F.4	Diets of native and nonnative Colorado River fishes	$46,002	$0	$0	$0	$0	$0	$12,881	**$58,883**
	Total F	**$467,043**	**$17,039**	**$37,583**	**$25,042**	**$0**	**$0**	**$153,078**	**$699,786**

G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$113,931	$4,000	$2,000	$0	$0	$0	$33,581	**$153,512**
G.2	Annual spring/fall HBC abundance estimates in lower 13.6 km of LCR	$15,488	$0	$14,200	$105,540	$342,506	$0	$48,139	**$525,873**
G.3	Juvenile chub monitoring near the LCR confluence (including July LCR monitoring trip)	$133,696	$0	$13,000	$267,151	$0	$0	$115,877	**$529,724**
G.4	Remote PIT tag array monitoring in the LCR	$46,303	$0	$6,000	$7,725	$0	$0	$16,808	**$76,835**
G.5	Monitoring HBC aggregation relative abundance & distribution	$14,100	$0	$14,100	$59,153	$96,240	$0	$27,346	**$210,940**
G.6	Juvenile chub monitoring - Western Canyon	$0	$0	$0	$0	$0	$0	$0	**$0**
G.7	Chute Falls translocations	$5,163	$0	$2,600	$16,615	$67,520	$0	$8,851	**$100,749**
	Total G	**$328,681**	**$4,000**	**$51,900**	**$456,184**	**$506,266**	**$0**	**$250,602**	**$1,597,633**
H	**Salmonid Research and Monitoring Project**								
H.1	Rainbow trout monitoring in Glen Canyon (AGFD)	$10,325	$0	$1,300	$14,291	$88,000	$0	$9,897	**$123,813**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$78,698	$5,000	$14,272	$86,471	$17,000	$0	$52,154	**$253,595**
H.3	Brown Trout Early Life Stage Survey (BTELSS)	$0	$0	$0	$0	$0	$0	$0	**$0**
H.4	Salmonid modeling	$58,389	$0	$1,500	$0	$43,000	$0	$18,059	**$120,948**
	Total H	**$147,413**	**$5,000**	**$17,072**	**$100,762**	**$148,000**	**$0**	**$80,109**	**$498,356**
I	**Warm-water Native and Non-Native Fish Monitoring and Research**								
I.1	System-wide native fish & invasive aquatic species monitoring (AGFD)	$10,325	$0	$6,000	$87,481	$217,550	$0	$35,592	**$356,948**
I.2	Invasion and colonization dynamics (includes AGFD invasive monitoring in LF)	$108,972	$0	$0	$7,047	$21,000	$0	$33,115	**$170,134**
I.3	Impacts of channel catfish in the LCR	$101,277	$0	$1,100	$0	$0	$0	$28,666	**$131,043**
	Total I	**$220,574**	**$0**	**$7,100**	**$94,528**	**$238,550**	**$0**	**$97,373**	**$658,125**
J	**Socioeconomic Research**								
J.1	Predictive models for adaptive management	$49,512	$1,500	$250	$0	$0	$0	$14,353	**$65,615**
J.2	Brown trout incentivized harvest	$77,018	$1,500	$1,250	$0	$24,500	$0	$23,070	**$127,338**
	Total J	**$126,530**	**$3,000**	**$1,500**	**$0**	**$24,500**	**$0**	**$37,423**	**$192,953**
K	**Geospatial Science, Data Management and Technology Project**								
K.1	Geospatial science	$184,541	$1,637	$1,400	$0	$0	$0	$52,522	**$240,099**
K.2	Database management	$161,242	$1,637	$700	$0	$0	$0	$45,802	**$209,381**
K.3	Remote monitoring and advanced technology	$46,231	$500	$1,600	$0	$0	$0	$13,533	**$61,864**
	Total K	**$392,014**	**$3,774**	**$3,700**	**$0**	**$0**	**$0**	**$111,857**	**$511,344**
L	**Overflight Remote Sensing in Support of Long-Term Monitoring and LTEMP**								
L.1	Overflight remote sensing	$181,637	$0	$0	$0	$80,596	$0	$53,276	**$315,509**
	Total L	**$181,637**	**$0**	**$0**	**$0**	**$80,596**	**$0**	**$53,276**	**$315,509**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$681,808	$20,000	$108,000	$0	$0	$0	$226,746	**$1,036,555**
M.2	Logistics staff	$273,839	$3,000	$0	$0	$11,000	$0	$77,845	**$365,684**
M.3	IT	$0	$0	$70,000	$0	$0	$0	$19,600	**$89,600**
	Total M	**$955,648**	**$23,000**	**$178,000**	**$0**	**$11,000**	**$0**	**$324,191**	**$1,491,839**

N	**Hydropower Monitoring and Research**								
N.1	Hydropower monitoring and research	$16,504	$1,500	$2,500	$0	$0	$0	$5,741	**$26,245**
	Total N	**$16,504**	**$1,500**	**$2,500**	**$0**	**$0**	**$0**	**$5,741**	**$26,245**
	GCMRC AMP Total (FY23)	**$4,292,234**	**$86,403**	**$404,246**	**$838,575**	**$1,502,680**	**$379,277**	**$1,619,089**	**$9,122,506**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$9,088,000**
	AMP Over/Under Budget								**-$34,506**
	Overflight Carryover: FY18-20 savings + logistics funding from 2022 cancelled trips								$0
	Anticipated Carryover Funding Available								$34,611
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								$107
	Lake Powell								
	Lake Powell (*current agreement expired*)	$0	$0	$0	$0	$0	$0	$0	**$0**
	GCMRC Grand Total (w/ Lake Powell)	**$4,292,234**	**$86,403**	**$404,246**	**$838,575**	**$1,502,680**	**$379,277**	**$1,619,089**	**$9,122,506**