Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2025-2027

Prepared in cooperation with the Glen Canyon Dam Adaptive Management Program

Prepared by

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

and

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

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

Investigators

David J. Topping[1], Ronald E. Griffiths[1], David J. Dean[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

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. Project A thus collects the physical data that directly link dam operations to all resources in the downstream 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 segment-scale sand mass-balance response to the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), and to evaluate the downstream effects of releases conducted under the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) (U.S. Department of the Interior, 2016a, b). Two of the metrics proposed to evaluate LTEMP management for sediment are measured by this project.

The data collected by Project A 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 (i.e., “Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes”), the 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 70% of the proposed budget covers basic data collection, with the remaining 30% supporting salaries for serving the data and for interpretive work (i.e., publications). The funds requested under this proposal cover ~80% of the costs required to collect surface-water, water-quality, and sediment data at the network of USGS gaging stations used by this project. An additional approximately $184,000 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 from funds provided by the Arizona Department of Water Resources. 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, 2021; Griffiths and others, 2024). The proposed monitoring under this project is a continuation of that conducted over the last 24 years. Work conducted under the previous work plan 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 (Topping and others, 2021; Griffiths and others, 2024). The work proposed in this current work plan is therefore that required to address this important conclusion.

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 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 (Project Element A.3) constructed using 15-minute streamflow data (Project Element A.1) and suspended-sand data (Project Element A.3). Although the second hypothesis guides data collection in Project A, this hypothesis is tested by the other GCDAMP-funded projects.

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, 2000a, b, 2003, 2021; Rubin and Topping, 2001, 2008; Gloss and others, 2005; Griffiths and others, 2024). 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; Rubin and others, 2020; Topping and others, 2021), 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; Voichick and others, 2018), 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 throughout the CRe (Hall and others, 2015; Deemer and others, 2022). 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/. Because water temperature, turbidity, and dissolved oxygen in the CRe are either controlled or regulated by operation of Glen Canyon Dam, dam operations thereby exert a strong control on gross primary productivity throughout the CRe (Deemer and others, 2022).

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 segment is maximized (Topping and others, 2019). Thus, effective management of eddy sandbars and associated resources in different segments of the CRe requires managers to know when finer sand is maximized in those specific segments 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; Yackulic and others, 2018). 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). Through turbidity, suspended sediment controls gross primary productivity throughout the CRe (Deemer and others, 2022).

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, 2021). 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, 2021). 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 the Interior, 1995, 1996). The 1995 EIS incorrectly assumed that sand transport was regulated only by changes in discharge (Rubin and others, 2002). Rather, the amount of sand that can be stored in each river segment in the CRe is controlled by the interaction of dam releases with the grain size of the sand on the bed (Topping and others, 2021).

Owing to the influence of changing 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, 2021; 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 based on 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 the natural sand supply to the CRe, and the remaining tributary sand supply to the CRe has been declining over time. By cutting off most of the sediment formerly supplied to the Colorado River in Marble and Grand canyons (Figure 1), 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, 2021). 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 (Dean and Topping, 2019, 2024), 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, 2024). 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 (*Gila cypha*) in the lower LCR (Unema and others, 2021). 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, 2021). 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, 2021). 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 most 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 ~63 days to transit Upper Marble Canyon (above river mile 30) and ~144 days to exit Marble Canyon (Topping and others, 2021). This result indicates that the most efficient rebuilding of sandbars in Marble Canyon will occur during HFEs conducted within 60 to 140 days after a large Paria River flood, except when dam releases are abnormally low such as during 2021 through early 2023 when low dam releases allowed for multi-year retention of Paria-supplied sand.

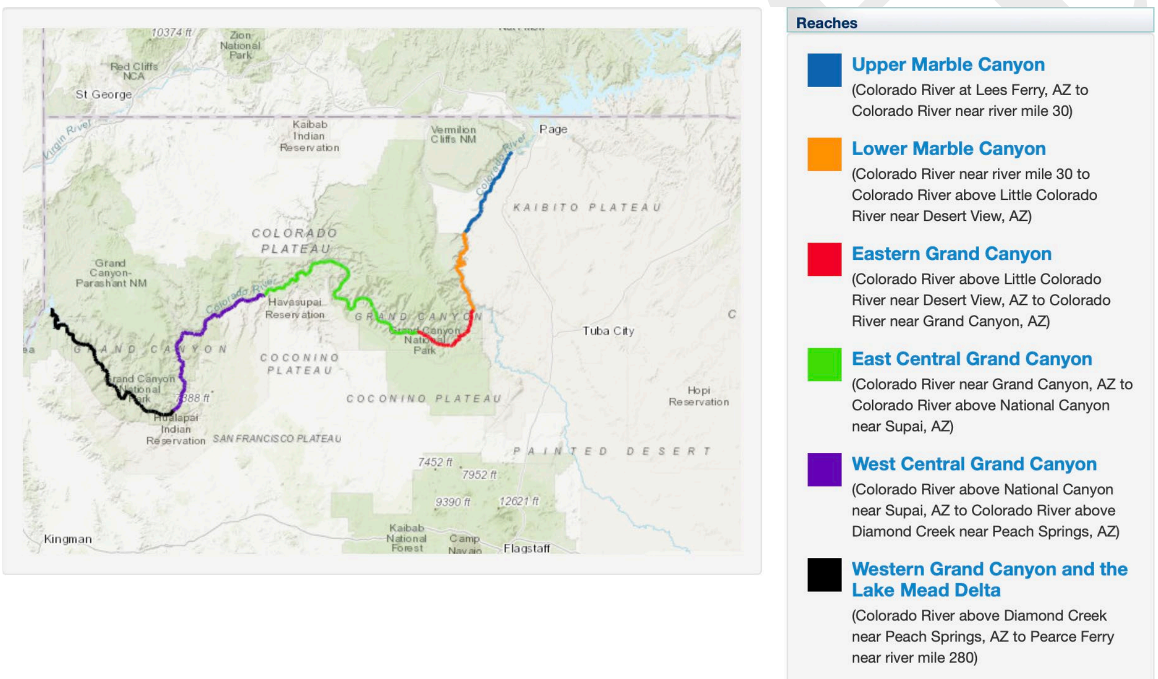

Figure 1. Map showing the extents of the six segments (a.k.a. reaches) of the Colorado River in Marble and Grand canyons in which mass-balance sand budgets are constructed. The seventh monitoring reach, lower Glen Canyon, lies upstream from Upper Marble Canyon. Map taken from Project A's website (U.S. Geological Survey, 2024).

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, based on Exner (1920, 1925) and Smith (1970), these measured gradients cause net sand deposition in some segments while they cause net sand erosion in other segments, 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, 2021). Thus, owing to downstream migration of tributary-generated sand waves in the CRe, the same dam operation will cause erosion in one segment while it causes deposition in another, with higher dam operations simply causing greater amounts of erosion or deposition in these segments.

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 segments in Grand Canyon may erode while upstream segments closer to the dam gain sand and *vice versa* (Topping and others, 2021). For this reason, and because of a large decline in the LCR sand supply, sand erosion has been recently more prevalent in downstream segments 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 (Figure 2; Topping and others, 2021). 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 ~13,400 ft^3/s (9.7 million acre-feet). 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 (10.2 million acre-feet). In lower sand-supply years, sand is eroded from Marble Canyon during years where the annual-mean discharge exceeds ~11,100 ft^3/s (8.0 million acre-feet) and from Grand Canyon when the annual-mean discharge exceeds ~11,300 ft^3/s (8.2 million acre-feet). Regardless of the magnitude of the Paria River sand supply, sand is eroded from Marble Canyon when the annual-mean discharge exceeds ~13,600 ft^3/s (9.8 million acre-feet). 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.

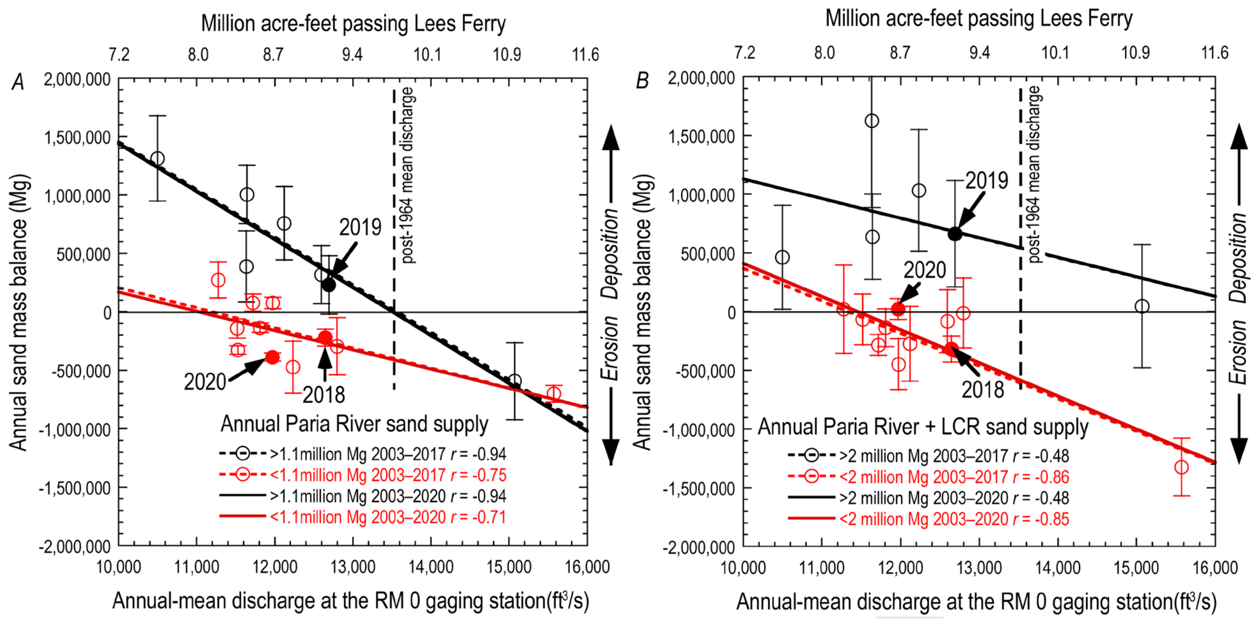

Figure 2. Figure modified from Griffiths and others (2024) Figure 2. Annual sand mass balance plotted as a function of annual-mean discharge and annual dam release (in acre-feet) at the Colorado River at Lees Ferry, AZ (RM 0) gaging station by sediment year (July 1–June 30) for (*A*) Marble Canyon and (*B*) Grand Canyon. Data are separated into relatively high (black) and relatively low (red) annual tributary sand supply. The sediment-year 2018–2020 values from Griffiths and others (2024) are depicted as filled circles, with each year labeled; values from previous years reproduced from Topping and others (2021) depicted as unlabeled open circles. The least-squares linear regressions fit to each sand-supply condition for the sediment-year 2003–2017 data from Topping and others (2021) are depicted as dashed lines; regressions fit to each sand-supply condition for all data from sediment years 2003–2020 are depicted as solid lines. Correlation coefficients (r) associated with each regression are shown. Error bars indicate the magnitudes of the uncertainties in annual sand mass balances propagated through equation 5 in Topping and others (2021). The post-1964 mean discharge is the mean discharge at the RM 0 gaging station during sediment years 1965–2020.

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 segments based on 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 segments (a.k.a. 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), trout management, and releases for smallmouth-bass suppression on sand resources throughout the CRe, and used in the design and evaluation of HFEs.

Comparison of our continuous mass-balance sand budgets with topographic-based sand budgets measured by Project B.2 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 April 2011 and May 2014, whereas our flux-based sand budget indicates 740,000±610,000 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 (Topping and others, 2021). The observed rates of increase in uncertainty over time in the Project A mass-balance sand budgets (Topping and others, 2021) indicate that the repeat mapping of the CRe conducted by Project B.2 should continue at least once-per-decade canyon-wide to verify Project A's evaluation of LTEMP sand management. To meet this canyon-wide requirement, individual mass-balance river segments (Figure 1) should be mapped at least once every three years to ensure the entire CRe gets mapped once per decade.

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 October 2008. 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).

Proposed Work

The work proposed herein is a continuation of that conducted under the previous work plan, with two key differences. The largest difference is that 10 pay periods of David Dean's salary has been shifted to Project C.4 (**currently proposed as unfunded in this work plan**) to lend his expertise to the important problem investigating how dam operations interact with the available sediment supply to help erode or anchor new vegetation.

The second difference is that funding previously within Project A for computer-science support for Project A's database and website has been shifted to Project K. As in all previous work plans, new interpretive products are planned to address the guiding hypotheses of how dam releases directly affect sediment and other resources in the CRe and to build on the conclusions of the work funded during FY 2021–24. The Project A data-collection network was developed and made progressively more efficient over the last 24 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 these parameters occur over timescales less than one hour (Figure 3; Wiele and Smith, 1996; Wiele and Griffin, 1998; Topping and others, 2000b, 2003, 2010; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010, 2014; 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. 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 the Interior, 2016a, b). The continuous mass-balance sand budgets provide the measurement-based "ground-truthing" of the Sand Mass Balance Index (SMBI) developed in Appendix E of the LTEMP EIS (U.S. Department of the Interior, 2016a). Higher values of the SMBI in the LTEMP EIS were taken as indicators of increased sand storage in the CRe, with increases in sand storage indicating an increase in the sand available to be deposited in sandbars during HFEs.

In addition, the 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 the Interior (2016a).

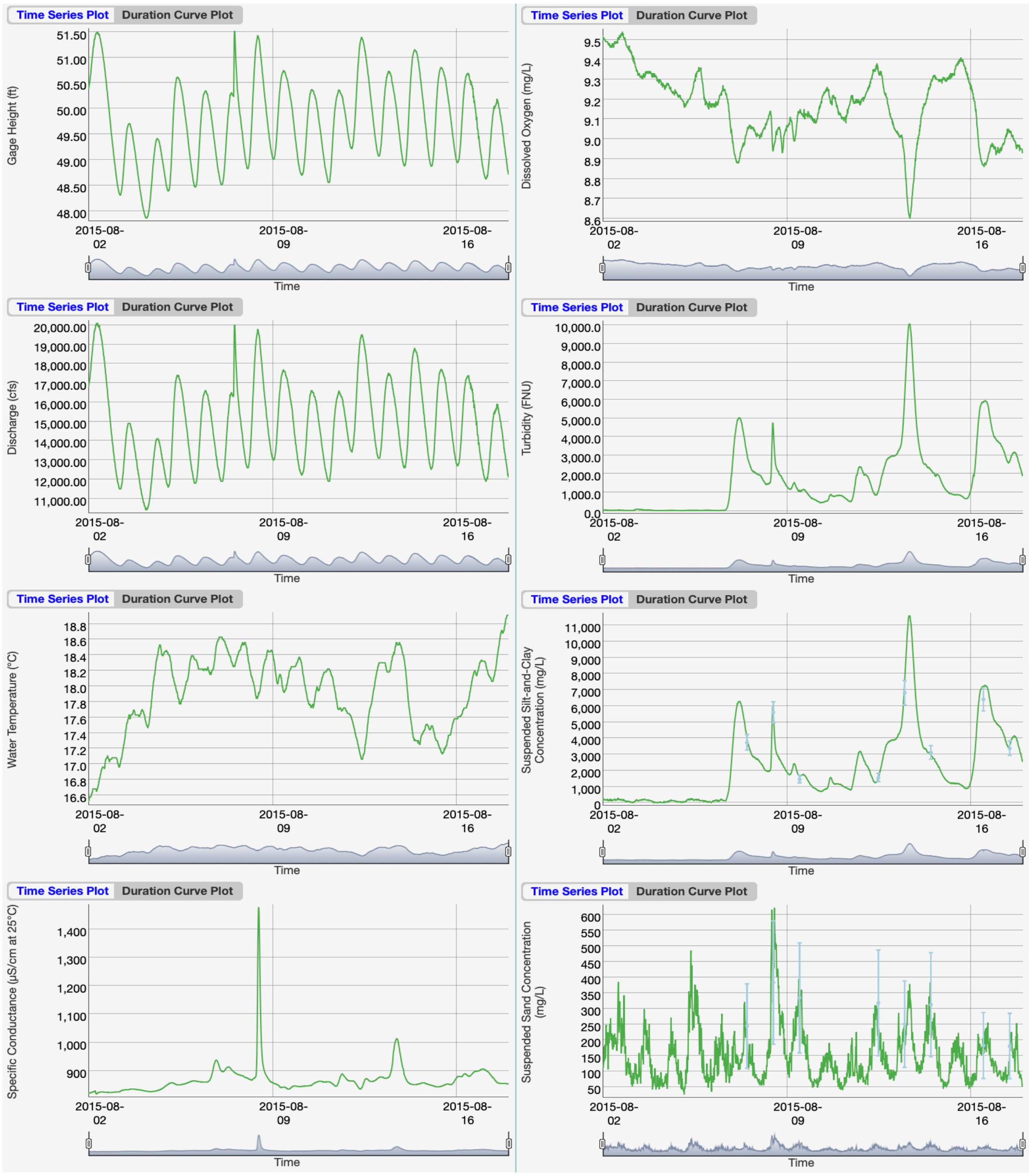

Figure 3. Plots of 15-minute gage height (i.e., stage, water elevation), water discharge, water temperature, specific conductance, turbidity, dissolved oxygen, suspended-silt-and-clay concentration, and suspended-sand concentration for the two-week period 8-2-2015 through 8-16-2015 at the Colorado River above Diamond Creek gaging station. Light blue dots with 95%-confidence-level error bars indicate episodically measured silt and clay concentrations and sand concentrations (from physical suspended-sediment samples) used to verify the two-frequency acoustical suspended-sediment measurements. Variability in each of these parameters over this two-week period arises from the interaction of dam operations with tributary floods. Plots from Project A's website at https://www.gcmrc.gov/discharge_qw_sediment/ (U.S. Geological Survey, 2024).

All data collected by Project A are served and can be downloaded at our website at: https://www.gcmrc.gov/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 segments, with user-defined uncertainty.

Project Elements

The following three project elements fund a large proportion of the salaries of 13 USGS scientists and technicians in the GCMRC, AZ Water Science Center, UT Water Science Center, and KS Water Science Center (database and website during FY 2025 before this work transitions to a GCMRC employee in Project K) and also fund smaller proportions of the salaries of 10 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. Eighty percent of the budget for Project 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.

Although the streamflow data collected under this element support GCMRC projects in every discipline (e.g., Korman and Campana, 2009; Kennedy and others, 2016; Neher and others, 2017; Deemer and others, 2022; Sankey and others, 2023; Butterfield and Palmquist, 2024), the data collected under this element are central to the LTEMP sediment goal and are used 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 (Yackulic and Hull, 2019; Unema and others, 2021) 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 and much of the work of Project G in the lower segment of the LCR critical for humpback chub habitat (Gorman and Stone, 1999; Unema and others, 2021). The suspended-sand flux is the product of the instantaneous water discharge and velocity-weighted suspended-sand concentration (Guy, 1970). This flux is augmented to account for sand bedload (Rubin and others, 2001; Topping and others, 2010, 2021; Ashley and others, 2020; LeCoz and others, 2022) and then integrated over time to calculate the sand load over any given time interval (Topping and others, 2021). These loads on the Colorado River and tributaries are used to construct the continuous mass-balance sand budgets described in Project Element A.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 Little Colorado River, 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, 2021). 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 an insufficient staffing level 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 FY 2025 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 and to monitor the hydrologic and water-quality conditions in tributaries most important for the aquatic foodbase (Project F.3) and fishes (Yackulic and Hull, 2019). 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 Project 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 (RM 0)*	AZ WSC	$0	Monitoring sand export from lower Glen Canyon during HFEs and other special LTEMP dam operations
Colorado River near river mile 30 (RM 30)	GCMRC	$15,000	15-minute sand loads used in sand budgets
Colorado River above LCR (RM 61)	GCMRC	$15,000	15-minute sand loads used in sand budgets
Colorado River near Grand Canyon (RM 87)*	AZ WSC	$0	15-minute sand loads used in sand budgets
Colorado R. above National Canyon (RM 166)	GCMRC	$9,000	15-minute sand loads used in sand budgets
Colorado R. above Diamond Creek (RM 225)	AZ WSC	$27,900	15-minute sand loads used in sand budgets
Paria River near Kanab	UT WSC	$20,700	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	$11,500	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	$30,600	NONE; used mainly by humpback chub studies
Kanab Creek above the mouth**	AZ WSC	$14,500	Event-based sand loads used to verify sand budgets
Havasu Creek above the mouth***	AZ WSC	$14,500	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	$8,200 (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	$8,200 (total for both)	Dean work monitoring 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.
***The surface-water record at this gaging station is partially funded by the Arizona Department of Water Resources.

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). Seventy-three percent of the budget for Project 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 augmented by other peer-review methods (Voichick and Topping, 2014; Voichick and others, 2018).

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. During high-silt-and-clay-concentration events, the turbidity data are corrected for false low readings (Voichick and others, 2018) and are extended to values higher than the detection limit of the optical turbidity probe using the acoustical suspended-silt-and-clay data collected under Project Element A.3 (Voichick and Topping, 2014). In addition to the water-quality data collected at the gaging stations on the Colorado River, 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.

Data collected under Project Element A.2 are routinely used in publications led by investigators in other GCDAMP-funded projects and investigators of projects external to GCDAMP (e.g., Yard and others, 2011; Hall and others, 2015; Korman and others, 2015; Ward and others, 2015, 2016; Yackulic and others, 2018; Yackulic and Hull, 2019; Dibble and others, 2021; Deemer and others, 2022; Dzul and others, 2023). The seasonal median turbidity in each river segment is the proposed metric used to evaluate LTEMP management for the silt-and-clay component of fine sediment. In addition, the turbidity data collected under this element are to be used in combination with the data and analysis from Project E.1 to estimate phosphorous in the CRe.

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. Eighty-one percent of the budget for Project 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, data collected under Project Element A.3 is coordinated with the phosphorous monitoring of Project E.1 in the Paria and Little Colorado rivers. The continuous silt-and-clay data collected under Project Element A.3 and continuous turbidity data collected under Project Element A.2 are to be used in combination with the data and analysis from Project E.1 and the turbidity modeling in Project B.4 (**currently proposed as unfunded in this work plan**) to estimate phosphorous in the CRe. 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 Project Element A.3 are made using standard USGS methods (Edwards and Glysson, 1999) augmented by additional peer-reviewed methods (Topping and others, 2010, 2011, 2016, 2021; Griffiths and others, 2012, 2014; Sabol and Topping, 2013; Sabol and others, 2022). Under this element, continuous two-frequency acoustical suspended-sediment measurements are made in the Colorado River at the gaging stations located at RM 30, 61, 87, 166, and 225 using the method of Topping and Wright (2016). In addition to informing river management in the GCDAMP, 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 segment 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 Project Element A.1. These measurements are used in conjunction with models (after Topping, 1997) to determine the near-realtime sediment inputs from the Paria and Little Colorado rivers used in sand budgeting (Topping and others, 2021). 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 (Griffiths and others, 2014; Griffiths and Topping, 2017; Topping and others, 2021). 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 provides funding for 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 (Sibley and others, 2015); funds within Project K provides additional funding for the computer-science support for this task. 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 the Interior, 2016a). HFEs are triggered and designed based on the Paria-supplied sand that accumulates in Marble Canyon during fall and spring implementation windows (U.S. Department of the 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 Project Element A.1) and initial model estimates (after Topping, 1997) to determine the near-realtime continuous sand supply from the Paria River (Topping and others, 2021). The Bureau of Reclamation and Project B.4 then use this information, along with information on planned dam releases, as input to the sand-routing model of Wright and others (2010) to design HFEs.

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 Project B.4 (**currently proposed as unfunded in this work plan**). As time progresses, the Project B.4 '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 by the Bureau of Reclamation. 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. The annual sand mass balance in each river segment is one of the proposed metrics used to evaluate LTEMP management for the sand component of fine sediment.

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 above Little Colorado River or Colorado River above Diamond Creek gaging stations. This work is required to verify HFE effects on sediment.

Outcomes and Products

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 (including those flows releases to suppress smallmouth bass). 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/).
2) Completion of journal article currently under preparation 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.
3) 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 Project 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 Project 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) Completion of a USGS professional paper describing the laser-diffraction measurements funded by the GCDAMP during FY 2001–10 and completion of a companion journal article focused on silt-and-clay grain size and flocculation (Topping leads). These papers have been under preparation for 10 years and will be completed during this funding cycle. Their content is central to the biological role silt and clay plays in the CRe.

3) Completion of a USGS report describing how all LTEMP dam releases (including possible balancing-tier or equalization releases) conducted during FY 2021–24 have affected the sand resources in the CRe on the segment scale (Griffiths lead). This report will update the results in Griffiths and others (2024), which described how all LTEMP dam releases affected sand in the CRe during FY 2018–20.

4) Progress or completion of a journal article or USGS report describing the conditions that lead to hyperconcentrated flows (Beverage and Culbertson, 1964; Topping, 1997) in the Paria River during certain floods (Griffiths lead). This work is required to better inform the Bureau of Reclamation in the HFE-planning and design process.

5) Progress or completion of a 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; work on this product began in the 1990s (Topping, 1997). All needed historical aerial photography was obtained and orthorectified under the last work plan.

5) Data from this element will be used in at least one presentation given by the scientists funded by Project 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 Project Element A.3 USGS report led by Griffiths.

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Budget

Fiscal Year 2025									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
A.1. Stream gaging and hydrologic analyses	$184,094	$6,000	$6,000	$27,000	$0	$174,800	$48,634	**$446,528**	
A.2. Continuous water-quality parameters	$116,673	$1,000	$12,000	$26,000	$0	$29,260	$33,937	**$218,869**	
A.3. Sediment transport and budgeting	$339,465	$6,000	$48,000	$26,200	$0	$154,360	$91,487	**$665,512**	
Total Project A	**$640,232**	**$13,000**	**$66,000**	**$79,200**	**$0**	**$358,420**	**$174,058**	**$1,330,910**	**$83,275**

Fiscal Year 2026									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
A.1. Stream gaging and hydrologic analyses	$196,981	$6,000	$6,000	$28,000	$0	$180,120	$53,558	**$470,658**	
A.2. Continuous water-quality parameters	$124,840	$1,000	$12,000	$26,800	$0	$30,080	$37,209	**$231,929**	
A.3. Sediment transport and budgeting	$363,227	$6,000	$48,000	$27,000	$0	$158,960	$100,395	**$703,583**	
Total Project A	**$685,048**	**$13,000**	**$66,000**	**$81,800**	**$0**	**$369,160**	**$191,162**	**$1,406,169**	**$89,633**

Fiscal Year 2027									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
A.1. Stream gaging and hydrologic analyses	$210,769	$6,000	$6,000	$29,000	$0	$185,800	$58,914	**$496,483**	
A.2. Continuous water-quality parameters	$137,577	$1,000	$12,000	$27,400	$0	$30,900	$41,647	**$250,524**	
A.3. Sediment transport and budgeting	$388,653	$6,000	$48,000	$28,000	$0	$165,900	$110,133	**$746,686**	
Total Project A	**$737,000**	**$13,000**	**$66,000**	**$84,400**	**$0**	**$382,600**	**$210,694**	**$1,493,693**	**$96,918**

Project B: Sandbar and Sediment Storage Monitoring and Research

Investigators

Paul E. Grams[1], Katherine Chapman[1], Matt Kaplinski[1], Gerard Salter[1], Shannon Sartain[1], Robert Tusso[1], Geodesist (vacant)[1], David Dean[1], Thomas M. Gushue[1], Erica Byerley[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Project Summary and Purpose

The purposes of this project are to a) track the effects of individual High-Flow Experiments (HFEs) on sandbars and campsites, b) monitor the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics. These objectives are accomplished by annual measurements at long-term sandbar monitoring sites (**B.1, proposed partially funded**), measurements of changes in riverbed sand storage and studies of riverbed dynamics (**B.2, proposed partially funded**), maintenance of a geodetic control network (**B.3, proposed unfunded**), and development of streamflow, sediment transport, and sandbar response models (**B.4, proposed unfunded**). Field activities that would occur for monitoring condition-dependent experimental actions such as HFEs are also described (B.5). Results from the monitoring elements of this project are used to evaluate progress towards meeting the Long-Term Experimental and Management Plan (LTEMP) goal, to "Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes." (U.S. Department of the Interior, 2016). The models developed and maintained in this project (**proposed unfunded**) are used to plan and design HFEs and to forecast the response of sediment and sandbars to potential flow scenarios for long-term planning.

The implementation of HFEs for building sandbars that is one of the central components of LTEMP is an extension of 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). The HFE Protocol 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? Expectations of improved deposition on sandbars and conservation of sediment were, therefore, among the criteria used in the selection of the preferred LTEMP alternative.

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, provide the information that is needed to proceed with or abort LTEMP experimental activities, evaluate the effectiveness of implemented experiments, and develop predictive models for future planning efforts. Additionally, these models are needed to evaluate ecological impacts of potential dam operations associated with habitat availability and turbidity.

The sandbar monitoring program described here was outlined in the LTEMP Science Plan (Vanderkooi and others, 2017) and provides the data required to compute the sandbar monitoring metric that will be used answer the fundamental question of the HFE Protocol and the 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. Because these long-term monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, Project Element B.2 includes periodic measurements of a larger sample of 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 sand supply metric, which 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 the volume and area of 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 of sandbar deposition to future HFEs to be similar or greater 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, which includes one channel mapping campaign. In this work plan, we will map the West-central Grand Canyon segment between River Mile (RM) 166 and 225 on one motorized trip in 2026.

There are two elements in Project B that are currently proposed unfunded. The Control Network and Survey Support element (**B.3, proposed unfunded**) has existed to support the development and maintenance of the geodetic control network in Grand Canyon that is used to reference all ground-based and remotely sensed geospatial measurements made by GCMRC. In the past, this element has supported a full-time geodesist, but that position is currently vacant. Potential paths forward and discussed in the project element description, below.

The Streamflow, Sediment, and Sandbar Modeling Project (**Project B.4, proposed unfunded**) includes maintenance and development of models for predicting sand mass balance, sandbar volumes, turbidity, and streamflow. The sand routing and sandbar models are used to compute the LTEMP performance metrics for sand mass balance and sandbars in a predictive framework and are thereby used for planning management actions such as HFEs and proposed changes in dam operations, including hourly, daily, monthly, and annual releases. If funded, this project would support developing a predictive model for turbidity, which is important for a variety of ecological processes, including gross primary productivity, phosphorous loads, and fish dynamics. This project element would also include development of a 2D streamflow model from central Marble Canyon (RM 30) to the Little Colorado River confluence (RM 61). This model will provide spatially resolved hydraulic information that is important for evaluating habitat availability and larval transport under different dam operations, and which will provide the groundwork for future morphodynamic models and coupled streamflow-vegetation modeling.

Several experimental components are included in Project B. These include additional sandbar surveys to evaluate condition-dependent experiments that affect sandbars and sediment resources, including extended-duration HFEs, proactive spring HFEs, and variations in HFE downramp rate, and potential nonnative fish management flows. Additional bathymetric surveys will be performed in the Western Grand Canyon study reach in the event of an HFE. We have also added an experimental element that would include substrate mapping between Glen Canyon Dam and Lees Ferry in response to a high level of interest in habitat in that reach.

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; Grams and others, 2019; Topping and others, 2021) and sand accumulates during periods of average dam-releases and substantial tributary sediment inputs (Grams and others, 2013; Grams and others, 2019). Sandbars along the riverbanks at elevations above average base flow stage (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; Hazel and others, 2022).

These deposits aggrade significantly during HFEs that exceed powerplant capacity and, to a lesser extent, during powerplant capacity flows (Schmidt and Grams, 2011; Hazel and others, 2022). These deposits typically erode during normal powerplant operations between HFEs (Hazel and others, 2010; 2022). 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 in planning documents, such as the LTEMP EIS (U.S. Department of the Interior, 2016). 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 and B.2)
    - 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? (Addressed in B.1 and B.2)
    - What is the long-term effect of dam operations, including controlled floods, on the total amount of fine sediment stored in the active river channel at low and high elevations? (Addressed in B.2)
    - How do these changes affect recreational 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? (Addressed in B.1 and B.4 (**proposed unfunded**) in conjunction with other projects)
- 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.4, **proposed unfunded**).
- How do current and proposed future dam operations affect turbidity, and can dam operations be modified to change turbidity levels sufficiently to benefit ecological resources? (Addressed in B.4, **proposed unfunded**)
- How do streamflow patterns associated with dam operations affect the distribution of aquatic habitat and larval transport? (Addressed in B.4, **proposed unfunded**)
- How does the interplay between patterns of streamflow, riparian vegetation, and sediment transport affect sandbar morphology and evolution? (Addressed in B.4, **proposed unfunded**)
- Do extended-duration HFEs result in larger or more numerous sandbars than HFEs less than 96 hours long? (Addressed in B.5.1) **(experimental fund)**
- Do proactive spring HFEs provide some mitigation of sandbar erosion in advance of high dam-release water volumes? (Addressed in B.5.2/B.5.3) **(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.5.4) **(experimental fund)**
- How does the river channel in Western Grand Canyon change in response to HFEs and other dam operations? (Addressed in B.5.5)

Relationship between Project Elements and LTEMP Goals

The above science and monitoring questions support LTEMP goals for sediment, recreational experience, archaeological and cultural resources, riparian resources, ecological goals, 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, B.2, and B.4. 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 and modeling of the area of bare sand available for transport by wind in Project Elements B.1, B.2, and B.4 support that work. Goals for riparian resources are addressed directly in Project C, but measurements of sandbars in B.2 support vegetation monitoring and modeling in B.4 supports future modeling of riparian vegetation. Monitoring in Western Grand Canyon as part of B.2 and B.5.5 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. Ecological goals listed in LTEMP are more directly addressed in other projects, but models for turbidity and spatially resolved streamflow are important for a variety of ecological processes, as described in B.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). Topping and others (2021) estimated a highly approximate lower bound for total sand erosion from Marble and Grand Canyons following the closure of Glen Canyon Dam of at least 28 million metric tons through 2017. Because systematic measurements of fine-sediment thickness have not yet been made, the total volume of fine sediment remaining 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:

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

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 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, 2019; Hazel and others, 2022). HFEs conducted with the HFE Protocol since 2012 have resulted in sustained, but not progressive, increases in sandbar area (Grams and others, 2019; Hazel and others, 2022). 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 HFE deposits, but decrease the area of exposed bare sand.

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 60% and 90% of the sand within HFE deposits is likely derived from the Paria River (Chapman and others, 2020), with the remainder composed of pre-dam sediment from the channel and its margins.

Paria-derived fractions as low as 25% were observed in some grain size classes for individual samples. Thus, a substantial proportion of the sand deposited during HFEs may be derived from background sand storage – the pre-dam sediment stored in eddies and the riverbed. Because higher concentrations of sand in suspension will result in greater rates of deposition during HFEs (Wiele and others, 1999), decreases in background sand storage – unless they are offset by tributary sediment inputs – will likely lead to diminished capacity to achieve one of the central LTEMP goals of rebuilding and maintaining sandbars using HFEs. Therefore, predictions about the long-term fate of sandbars must be based on understanding long-term trends in ΔS, including both ΔS_{low} and ΔS_{high}. For these reasons, the sandbar research and monitoring is designed around this concept of the sediment budget.

The measurements of suspended sediment made in Project A track the inputs and outputs (I and O in equation (1)) and are used to calculate ΔS for the sediment budget 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. Moreover, 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 (Figure 2).

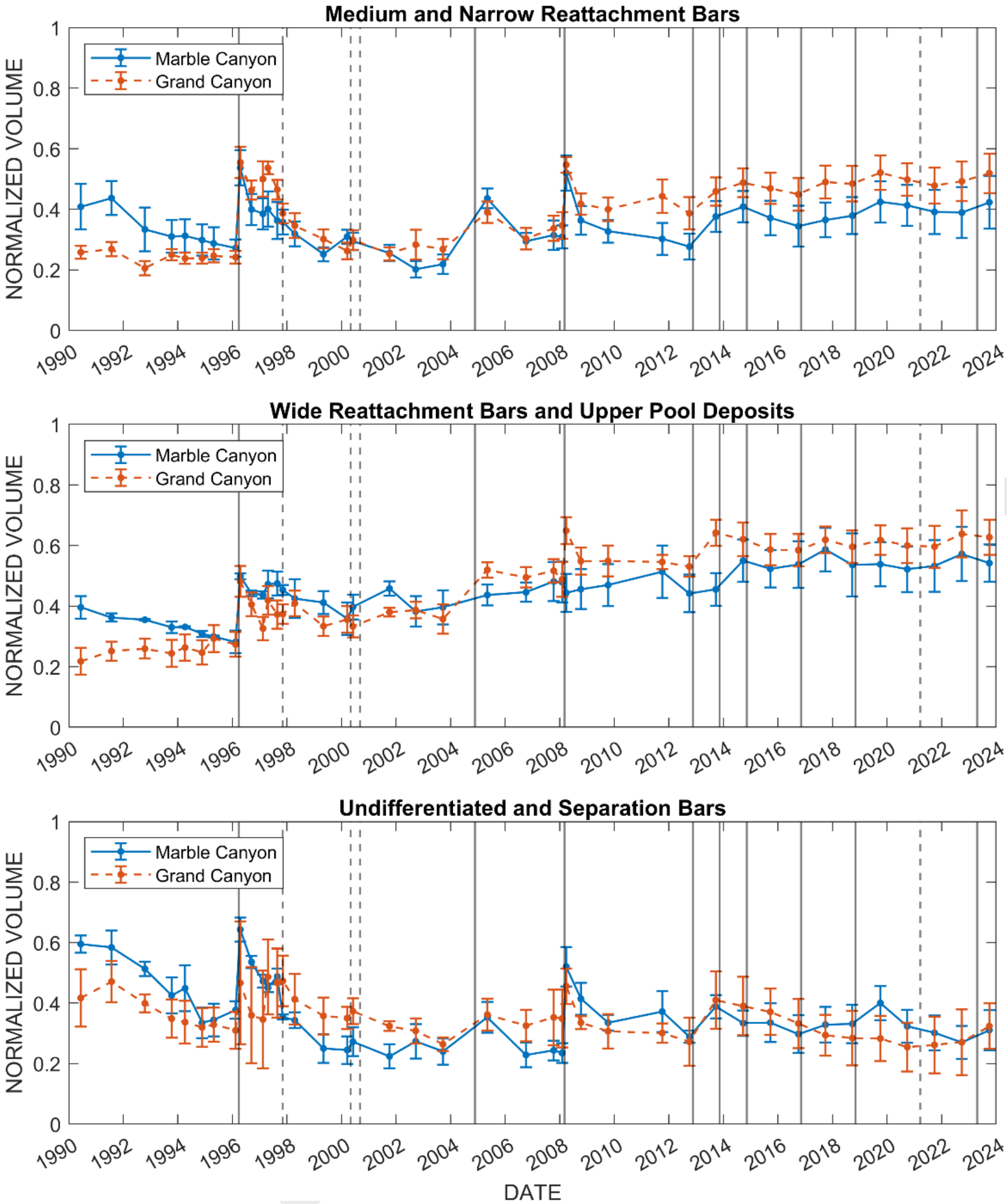

Figure 1. Normalized sandbar volume from 1990 to October 2023. The data are normalized and segregated by bar type, described by Mueller and others (2018).

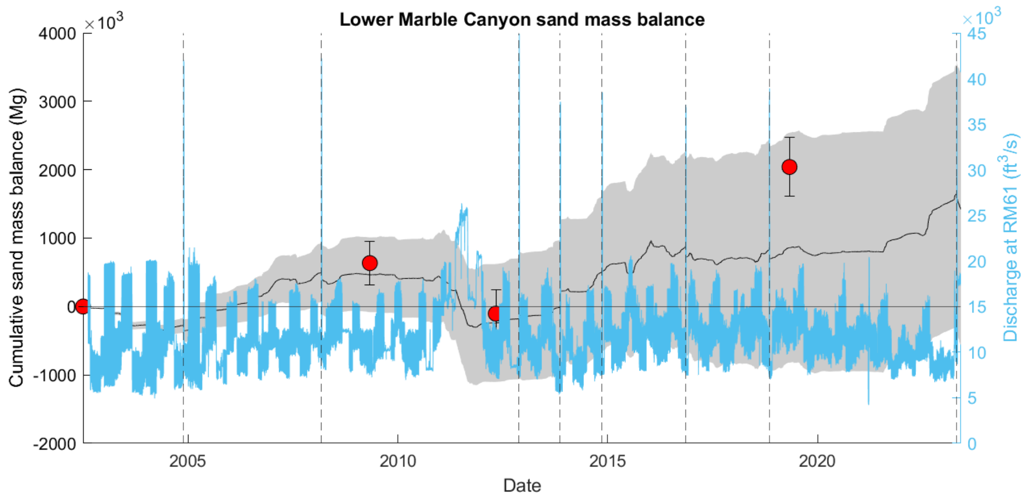

Figure 2. Mass balance sand budget for Lower Marble Canyon from August 2002 to December 2022. The black line shows the mass balance computed from continuous measurements of sediment flux measured by Project A with uncertainty shown by the gray shaded region. The red circles show the mass balance for the same river segment computed from repeat measurements of riverbed elevations measured by Project B.2. These data illustrate the necessity of the Project B.2 measurements of riverbed elevation to compute sediment storage changes over time periods greater than approximately five years. Data from Topping and others (2021), Grams and others (2013), Grams and others (2019), and unpublished data.

Previous studies analyzing repeat topographic measurements of the channel, eddies, and sandbars have found that 90% or more of the changes in sand volume occur at low-elevation, and that high-elevation sandbars comprise only about 10% or less of the fine sediment in the system (Hazel and others, 2006). These studies have also found that ΔS computed for short study reaches yielded different values than ΔS computed as the difference between sand inflows measured at gaging stations using equation (1). This discrepancy stems from the inability to correctly extrapolate measurements from short reaches to larger spatial scales because changes in bed topography are highly localized and spatially variable (Grams and others, 2013; 2019). These findings demonstrate that determining whether sediment storage in each storage environment – at low and high elevations and in the channel and eddy – is increasing, decreasing, or stable requires repeat measurements of sand storage in a large sample of the storage environments within each of the long sediment-budgeting reaches.

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, 2019). 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 their interpretation will increase.

Figure 3 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 bar sand (ΔS_{high}) compared to sand thickness change in the bed sand in eddies and the channel (ΔS_{low}), using data collected in Upper Marble Canyon (UMC), Lower Marble Canyon (LMC) and Eastern Grand Canyon (EGC). The figure also contrasts changes that occur during HFEs with changes that occur over long time periods. The plot is divided into four quadrants based on relative changes in sand on the bed and sand in sandbars and each quadrant management implication.

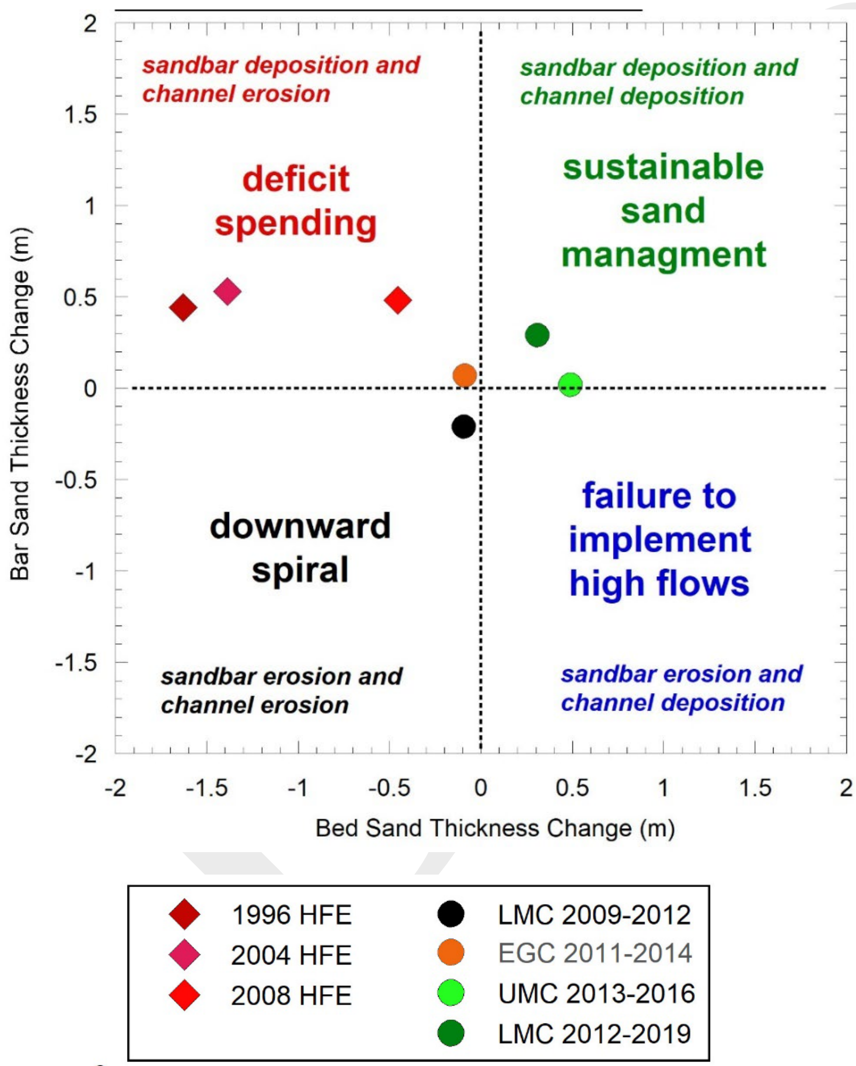

Figure 3. Change in high-elevation sand (sandbars) as a function of change in low-elevation sand (eddy and channel) based on repeat measurements in Upper Marble Canyon (UMC), Lower Marble Canyon (LMC) and Eastern Grand Canyon (EGC). The diamonds show measurements made at individual study sites before and after high-flow experiments (HFEs). The circles show measurements made over the indicated periods for entire ~50-km river segments. 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. Data from Schmidt and Grams (2011), Grams and others (2013), Grams and others (2019), and unpublished data.

Sandbar deposition accompanied by erosion in the channel (upper left quadrant of Figure 3) 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. This occurred in EGC between 2011 and 2014, which included a period of sustained high releases from Glen Canyon Dam. Despite the decrease in supply, sandbars increased because HFEs were implemented in 2012 and 2013. The worst case or “downward spiral” scenario is erosion of high-elevation sandbars accompanied by erosion of low-elevation sand in the channel (lower left quadrant of Figure 3). This occurred in LMC between 2009 and 2012, which included the same period of sustained high releases, but did not include any HFEs. In this case, changes to dam operations such as reducing maximum monthly releases would need to be considered. If changes to operations alone were insufficient, sediment augmentation might become necessary to restore the system to the “sustainable sand management” quadrant (Randle and others, 2007).

The Project B.2 measurements indicate that sustainable sand management (upper right quadrant of Figure 3) has occurred over some periods for some river segments. This occurred in both UMC and LMC for periods that included HFEs and did not include sustained high reservoir releases. One of the objectives of LTEMP is to learn whether this pattern of sustainable sand management can be achieved over long (~20-year) periods. If the measurements made in Project B.2 show this pattern repeatedly, that would indicate that sandbar building and sediment conservation goals are likely being met and, furthermore, that sand supply could support increases in HFE frequency and/or duration.

Finally, sandbar erosion accompanied by sand accumulation in the channel (lower right quadrant of Figure 3) would indicate that despite adequate sand supply, sandbar maintenance goals are not being met. This would suggest that more frequent or longer duration HFEs might be required to achieve different results. 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 unknown, and it will not be possible to identify the appropriate management response.

Proposed Work

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

The purpose of this project element is to monitor the annual status and long-term trends of sandbars and campsites in Glen, Marble, and Grand Canyons. The results will be used to evaluate the effects of dam operations, including HFEs, on sandbars and related resources and will include reporting of the sandbar performance metrics for LTEMP. We will continue annual measurements at 45 long-term monitoring sites with topographic surveys (Hazel and others, 2022) that will be used to compute sandbar area and volume at all sites (Figure 1) and usable campsite area (Hadley and others, 2018) at a subset of 37 sites.

These sites were selected between 1990 and 2002 to represent the range of sandbar types with sites distributed throughout Marble and Grand Canyons such that measurements can be made at all sites on a single annual river trip. Although these study sites comprise less than 10 percent of the subaerially exposed sandbars of similar type in all of Grand Canyon (Hazel and others, 2022), they have been shown to be representative of a larger sample of sandbars of similar type in Lower Marble Canyon and Eastern Grand Canyon (Hazel and others, 2022). The degree to which these monitoring sites are representative of sandbars in Western Grand Canyon where sites are more sparsely distributed is poorly known. Additionally, these sites do not represent the narrow, river-parallel, deposits of sand that occur outside of eddies which are used infrequently for camping. We will evaluate replacing up to three of the sites that are no longer sensitive to dam operations owing to vegetation expansion with sites that may be of greater interest, such as sites that have active vegetation management programs in place. This project will also include maintenance of remote cameras for daily monitoring at 42 sites (Grams and others, 2018). The methods for data collection, processing, and analysis are described in detail by Hazel and others (2022). In brief, each site is surveyed using conventional survey methods with electronic total stations. Lidar or photogrammetric methods (airborne or ground based) are not practical because they do not reliably penetrate the dense vegetation or measure submerged topography. The submerged topography must be surveyed to consistently measure down to the elevation that is inundated by discharges of 8,000 ft^3/s. The topographic surveys are processed to create digital elevation models (DEMs) for each site for each year. The DEMs are compared among all years to create annual metrics for sand volume and area in two zones: 1) the zone that is inundated by discharges above 8,000 ft^3/s and less than 25,000 ft^3/s and, 2) the zone that is inundated by discharges above 25,000 ft^3/s and below 45,000 ft^3/s. All analyses are performed in a processing workflow that includes open-source processing scripts and stores the results in a database. The database is linked to a website that serves the sandbar data and images from the remote cameras (U.S. Geological Survey, 2024, https://www.usgs.gov/apps/sandbar).

Data collection for this project will occur on one non-motorized river trip each year. In cooperation with Project C, we will continue to investigate the interactions between sandbars and vegetation by working on a coupled model for sandbar and vegetation change (contingent on funding for C.4). This information could be used to understand why some sites are more or less likely to have vegetation expansion and could also be used to choose sites for vegetation management. This project also includes support for the Grand Canyon River Guides Adopt-a-Beach program, which provides an assessment of campsite condition from the perspective of river guides based on repeat photographs, which are available on the GCMRC website (https://www.usgs.gov/apps/sandbar). In the third year of this work plan, we will prepare a summary report describing the response of sandbars to dam operations focusing on the period from 2020 to 2026 because the last major report on sandbars included analysis of data through 2020 (Hazel and others, 2022).

If the LTEMP experiment to study an HFE with lower downramp rate (U.S. Department of the Interior, 2016) is implemented, we will investigate the impact of HFE hydrograph shape on sandbar morphology. Because this work is contingent on the implementation of the experiment, funding for logistics and data analysis are in Experimental Project Element B.5.

Support in the form of database and website management, preparation of map books for field work, and geographic information systems (GIS) technical support is provided by Project K.

Project Element B.2. Bathymetric and Topographic Mapping for Monitoring Sediment Storage and Riverbed Dynamics (partially funded)

The primary purpose of this project element is to track trends in sandbar conditions and sand storage over the time scale of LTEMP to provide an evaluation of whether the supply of sand (the sum of recent tributary inputs and background storage) necessary for building sandbars is increasing, decreasing, or stable and a robust measure of high-elevation sandbar change. The results will be used to evaluate the outcome of the flow regime adopted in the LTEMP with respect to sandbar building and sand conservation (Figure 3). The monitoring data will also be used to compute LTEMP performance metrics for high-elevation sandbars and sand mass balance by river segment (Figure 2). Changes in sand storage are tracked over long river segments, providing a spatially explicit quantification of changes in the channel, eddies and sandbars (Grams and others, 2013; 2019). The sandbar measurements made in Project Element B.2 include a much larger sample of sandbars than included in the B.1 annual sandbar monitoring. Additionally, measurements of sand storage in the river channel are critical because that information will be needed to explain the observed trends in sandbar area and volume and whether HFEs should be conducted more frequently or less frequently than prescribed in the LTEMP. This information will also be needed to assess whether the implemented flow regime is able to achieve sediment-related goals with the available sediment supply, or whether additional management actions should be considered. Additionally, this project includes mapping of riverbed substrate composition and studies of riverbed dynamics in response to HFEs and dam operations. Results from these studies are used to better understand aquatic habitat and how dam operations affect riverbed conditions in specific river segments.

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 Colorado River ecosystem (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 and compare the changes that occur in the channel, eddies, and on sandbars with the measurements of sand transport (Figure 2). 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, 2019). Because about 90% of the sand that is available for redistribution by dam operations is submerged (Hazel and others, 2006), the monitoring method must include measurements of sediment on the bed of the river in eddies and pools. Bed sediment data collection will combine multibeam and singlebeam sonars, coupled with conventional topographic surveys for areas above the water surface. All data are referenced to a Grand Canyon geodetic control network and because global navigation satellite system positioning is unreliable in the narrow and deep canyon, positioning is achieved by shore-based range-azimuth robotic tracking instruments (Kaplinski and others, 2017a, b). These methods have been described by Hazel and others (2008; 2010) and Kaplinski and others (2014; 2017a, b; 2022b). The data will result in high-resolution Digital Elevation Models (DEMs) of the mapped reaches for each mapping effort (e.g., Kaplinski and others, 2017a, b; 2020; 2022a).

Because uncertainty in the flux-based mass balance increases to cause an indeterminate budget in 5 to 10 years (Figure 2), a repeat interval of 10 years or less is required to track the sediment supply. A repeat interval of 5 to 7 years for most segments was proposed in the previous work plan, because that would provide the most certainty in tracking the sediment supply. That schedule would require data collection for at least one of the five segments nearly every year. In this work plan we propose to extend the target repeat interval to ~10 years for each segment (Table 1). A 10-year repeat interval can be accomplished by collecting data in one segment every other year, reducing logistics costs but still meeting the needs for LTEMP monitoring.

For this three-year work plan, we propose to conduct repeat bathymetric and topographic mapping for the segment between RM 166 and 225 on one motorized trip in the three-year work plan (in FY 2026). The next three-year work plan (FY 2028-30) will require two mapping efforts to stay on the 10-year repeat interval schedule (Table 1). In years without data collection, project personnel will focus on data processing, analysis, and reporting. In FY 2025, we will conclude analysis and reporting on data collected in Upper Marble Canyon in 2024 and in FY 2027, we will report on the data collected in 2026.

Table 1. Proposed schedule of channel mapping efforts for this work plan through the period of the Long-Term Experimental and Management Plan (LTEMP).

Segment	River Miles	Completed Surveys	Next Planned Survey	Interval to Next Survey
1) Glen Canyon	-15 to 0	2000, 2015	research only	--
2) Upper Marble Canyon	0 to 30	2013, 2016, 2024*	2034	10 yr
3) Lower Marble Canyon	30 to 61	2009, 2012, 2019	2028	9 yr
4) Eastern Grand Canyon	61 to 87	2011, 2014, 2019	2030	11 yr
5) East-central Grand Canyon	87 to 166	2022**	2032	10 yr
6) West-central Grand Canyon	166 to 225	2017	**2026*** **	9 yr
7) Western Grand Canyon	225 to 280	none	research only	

* Was planned for 2023, but funding was not available until 2024.

** Was planned for 2021, be rescheduled for 2022 to avoid overlap with 2021 overflight.

*** Only survey included in this 3-year work plan.

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).

Some aspects of B.2 have been proposed as unfunded to reduce the budget and are described in the following paragraph.

Because the overflight is currently proposed as unfunded in Project L, we removed the ground-truth data collection, which would have included a measurement of the water surface and riverbed profile on a motorized trip during the proposed overflight.

We also proposed to map riverbed substrate in the segment between Glen Canyon Dam and Lees Ferry and investigate the potential for detecting and mapping smallmouth bass nests in that reach. In addition, we proposed continued evaluation of riverbed response to dam operations in Western Grand Canyon that was initiated in the FY 2021-23 work plan (preparation of a report on that work is in progress). This work was proposed to include annual monitoring of the 3-mile study reach that begins at River Mile 273, development of a sediment budget for Western Grand Canyon, and monitoring the stability of Pearce Ferry Rapid. Pearce Ferry rapid is a barrier to fish migration and changes could have significant ecosystem implications. Comparison of photographs taken from 2021 to 2024 indicate the rapid has likely eroded, but the magnitude of erosion is unknown. Additional monitoring of this reach may occur as part of Experimental Project Element B.5.5, which includes additional surveys bracketing HFEs.

Support in the form of database and website management, preparation of map books for field work, and geographic information systems (GIS) technical support is provided by Project K.

Project Element B.3. Control Network and Survey Support (proposed unfunded)

The purposes of this project element are to establish and maintain the framework for high-accuracy change detection. This project element ensures that geospatial data collected across all projects of the program are accurately referenced, precisely defined, and can be reliably compared with past and future datasets. This project has been included as an element in Project B for the past several work plan cycles because much of the work in expanding the control network was done in cooperation with other Project B elements. Because this expansion of the control network is largely complete and future work will focus on maintenance of the network, documentation, and database management, we are considering migrating this project element to the Geospatial Science Project (Project K) in future work plans.

Knowledge of the accuracy associated with geospatial data sets produced from disparate sources is required for decision making based on long-term resource monitoring. The accuracies of each data set are determined by comparison with independent sources of higher accuracy referencing a common datum (or geospatial reference system). An accurate geodetic control network provides access to the common datum for change detection, the means to validate the accuracy of subsequent data products and ensures that spatially referenced observations are repeatable. For example, the merging of LiDAR (light detection and ranging remote sensing), sonar, digital imagery, and total station measurements along a reach of river requires consistent reference, especially because each are measured from different locations. This project element ensures that these and other data products can be precisely aligned. As such, the ability to provide accurate positions and determine product accuracy benefits several projects including the Streamflow, Water Quality, and Sediment Transport and Budgeting (Project A), Sandbar and Sediment Storage Monitoring (Project B), Riparian Vegetation (Project C), Geomorphic Effects of Dam Operations (Project D), Geospatial Science and Technology (Project K), and Remote Sensing Overflight (Project L).

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

Currently, nearly all of the river corridor from GCD to Diamond Creek has a sufficient number of control points to support monitoring activities.

Recently, the United States implemented the North American Terrestrial Reference Frame of 2022 (NATRF2022), replacing the North American Datum of 1983 (NAD83) as the official Federal datum (National Geodetic Survey, 2019). 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 were developed and published in an open forum so all prospective users will have access. These grid coordinate systems were 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).

The Grand Canyon control network was developed and has been managed by a full time Geodesist for the past 26 years, however that position is currently vacant. Full funding of this project element would enable GCMRC to refill that vacancy with a full-time Geodesist to continue management of the control network. As an alternative, partial funding (~50% or more) would enable GCMRC to establish a contract or cooperative agreement with a Geodesist. For this scenario, the objectives for this three-year work plan would be to complete a report summarizing the status of the control network, complete a data release that documents all control points in the current network and their uncertainties, and develop a plan for migrating to use of the new spatial reference frames (NATRF2022) and maintaining the control network in the future.

Project Element B.4. Streamflow, Sediment, and Sandbar Modeling (proposed unfunded)

The purposes of this project element are to maintain and continue development of sediment routing (sand, silt, and clay) and sandbar response models and to begin development of a new streamflow model for the Colorado River between (RM 0) and Phantom Ranch (RM 87); in this TWP, model development will occur between RM 30 and RM 61. We will begin with this river segment because it has the best constraint on boundary conditions for both streamflow and sediment transport (U.S. Geological Survey, 2024a; https://www.gcmrc.gov/discharge_qw_sediment). This segment also contains two of the several known aggregations (Valdez and Ryel, 1995) of humpback chub (*Gila cypha*) and is therefore of interest for aquatic habitat. These aggregations are river segments where humpback chub are typically found in greater abundance and extend approximately from RM30 to RM 36 and RM 57 to RM 77 (Persons and others, 2017). These models will serve a variety of purposes within GCDAMP. The sand routing and sandbar models are used to compute the LTEMP performance metrics for sand mass balance and sandbars in a predictive framework and are thereby used for planning management actions such as HFEs and are also used to evaluate the potential outcomes of proposed changes in dam operations, including hourly, daily, monthly, and annual releases. We will continue development of a silt and clay-routing model for predicting turbidity, which is important for predicting gross primary productivity, phosphorous loads, and fish population dynamics (including nonnative smallmouth bass [*Micropterus dolomieu*]). Finally, the new streamflow model will provide spatially explicit predictions of water depth, velocity, and shear stress at different discharges and is needed to quantify habitat characteristics for aquatic organisms and larval transport. This streamflow model will also provide the groundwork for future morphodynamic models for sediment transport and sandbar dynamics, and modeling interactions between streamflow and riparian vegetation (Project C.4).

The Sand Routing Model (Wright and others, 2010) is used as part of the LTEMP planning process to determine the appropriate HFE duration based on predicted sand mass balance. This modeling has in the past been performed by Reclamation, but since Fall 2022 has been done by GCMRC. Because this is a data-driven empirical model, regular model verification and recalibration are necessary and are provided through this project element. Model predictions will continue to be validated against sand mass balance predictions generated through Project A.3, and if necessary, we will perform recalibration of the model.

The Sandbar Model (Mueller and Grams, 2021) is a semi-empirical model used to predict sandbar volume through time in response to dam operations and can be used to evaluate the potential outcomes of management actions such as HFEs, as well as proposed changes in dam operations, including hourly, daily, monthly, and annual releases.

We anticipate that the Sandbar Model will be particularly useful for decision makers in GCDAMP if proposed changes to the sediment accounting window under the LTEMP SEIS are implemented, as it can provide quantitative predictions of sandbar volume change associated with fall HFE implementation vs. deferring to spring.

Additional improvements to the Sandbar Model are needed to realistically predict sandbar responses to different proposed dam operations. In the current version of the Sandbar Model, the deposition rate is based on Andrews and Vincent (2007), and accounts for the impacts of variations in stage, discharge, and sediment concentration on the deposition rate. However, the erosion model is highly simplified, assuming that the erosion rate is proportional to sandbar volume and is independent of discharge. Prior sandbar surveys have shown that high monthly releases accelerate sandbar erosion (Hazel and others 2022), and Alvarez and Schmeeckle (2013) found that discharge fluctuations accelerate sandbar erosion through seepage erosion. Neither of these effects are included in the current version of the Sandbar Model, making it more difficult to interpret predictions of the model for future flow scenarios. Additionally, the Sandbar Model is currently calibrated based on the group 1a bar type (Mueller and others, 2018), a small subset consisting of nine out of forty-five of the sandbars that are included in the long-term monitoring (Project B.1). In particular, the current Sandbar Model does not include vegetation, and therefore is unsuitable for bar types with high vegetation cover. In this work plan, we will 1) improve erosion relations used in the sandbar model to better predict the effects of dam operations on sandbar volumes, 2) collaborate with project C to incorporate vegetation effects (that is, increased deposition, and decreased erosion) on sandbars, and 3) calibrate multiple versions of the model to capture the potentially disparate effects of operations on different bar types.

Development of new streamflow models for the reach between RM 0 and RM 87 is needed because existing models (Wiele and Griffin, 1997; Magirl and others, 2008; Mihalevich and others, 2020) are based on estimated “synthetic” channel geometry, and are limited to a single spatial dimension, which means that while they can reliably predict discharge, they cannot be used to predict water depths, streamflow velocity, or bed shear stress. Predictions of these quantities are necessary for spatially explicit predictions of sediment, nutrient or veliger transport, and quantification of physical habitat for fishes, riparian and in-stream vegetation, and invertebrates (including mussels). We propose to develop and calibrate a two-dimensional, hydraulic model for Marble Canyon and Eastern Grand Canyon, where extensive channel mapping data are available; in this TWP, the initial model construction will occur between RM 30 and RM 61. The model will be used to provide the necessary boundary conditions required to run and validate morphodynamic sandbar models which are required to better understand the feedbacks between vegetation encroachment and sandbar dynamics, and to provide flow depth and velocity relations for habitat characterization. A similar model was developed for the reach between Glen Canyon Dam to Lees Ferry (Wright and others, 2024) that has proved useful for a range of ecosystem studies, such as quantifying available smallmouth bass nesting habitat at different discharges.

The streamflow model will use bathymetry and near-channel topographic data collected during previous channel mapping trips, along with topography above the 8,000 ft^3/s stage collected during the 2021 aerial overflight. Because there are some unsurveyed river sections (i.e., rapids and shallow riffles), we will assess model sensitivity to different approaches for estimating bathymetry in those reaches. The modeling domain from RM 30 to RM 61 complements the previously developed two-dimensional streamflow model for Glen Canyon (Wright and others, 2024). Like the Glen Canyon model, the RM 30 – RM 61 streamflow model will be constructed within the International River Interface Cooperative (iRIC) software using either the Flow and Sediment Transport with Morphologic Evolution of Channels (FaSTMECH) solver or the Nays2DH solver which has morphodynamic modeling capabilities. Roughness parameters within the model will either consist of Manning's n, or the z_o roughness coefficient which is based on the bed-sediment grain size and is not sensitive to fluctuations in discharge like Manning's n. The model will be calibrated using surveyed water level profiles at 8,000 ft^3/s along with established discharge/stage relations at sandbar monitoring sites. The effects of vegetation in the Glen Canyon model were not specifically modeled and will be a key component within the new streamflow model between RM 30 and RM 61, such that the effects of vegetation on shoreline flow velocities and shear stress can be determined. These vegetation effects will help guide vegetation management actions within Marble and Grand Canyons. The streamflow/vegetation interactions will be analyzed within Project C.4 (**proposed unfunded**).

The turbidity modeling component of this project element will be valuable for predicting gross primary productivity (Deemer and others 2022; Project E.2), phosphorous loads (Project E.1), and interpreting fish population dynamics (including smallmouth bass, see Project I.4, currently proposed unfunded) (Hansen and others, 2023). Preliminary results from project E show a strong and significant correlation between total phosphorous loads with silt/clay concentrations in the Colorado River mainstem and tributaries. Additionally, turbidity can reduce the vulnerability of juvenile native fishes to predation by nonnative fishes such as brown trout (*Salmo trutta*) and smallmouth bass (Ward and others, 2016; Ward and Vaage, 2019, Schmidt and others, 2024). Turbidity in the Colorado River is dominantly controlled by silt and clay, and to a lesser extent fine sand. We will continue to work on a new fine sediment (silt and clay) routing model that was started in the FY 2021-23 work plan. This modeling highlighted the importance of eddies in controlling silt/clay routing following tributary floods, and predicted deposition of a small fraction of the supplied silt/clay within the bed and eddy sandbars, which was gradually released as a function of subsequent dam operations. In this work plan, we will 1) refine calibration parameters to better predict silt, clay, and fine sand routing, 2) develop empirical relationships to translate model predictions of sediment concentration to turbidity, and 3) develop refinements to improve model runtime so that it can be used in future scenario-testing, similar to how the sand routing model was used in the LTEMP SEIS. We will work with Projects E and I to incorporate our results into predictive models for gross primary productivity, phosphorous loads, and fish population dynamics.

Project Element B.5. Sandbar and Riverbed Response to Experimental Actions (proposed to be funded only when experiments occur)

The LTEMP Environmental Impact Statement and Record of Decision (U.S. Department of the Interior, 2016) included two experimental activities in addition to regular fall and spring sediment-triggered HFEs designed to improve sandbar and sediment resources (extended-duration HFEs, proactive HFEs, and variation in HFE downramp rate) and one experimental activity that may cause increased sandbar erosion (trout management flows). Additionally, although not described specifically in the LTEMP ROD, experiments that involve adjusting the downramp rate of an HFE while maintaining a hydrograph within the parameters of the LTEMP ROD may be conducted. GCDAMP stakeholders have also proposed evaluation of 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 that will be used to evaluate the effects of any of those flow experiments on sediment resources if those experiments 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, processing, and analyses of those data.

Project Element B.5.1. 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 (Project Element B.4) to evaluate the predictive capability of the modeling approach.

Project Element B.5.2 and B.5.3. 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.5.2).

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.5.3). 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.5.4. 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 determined based on the total modeled change in sand mass balance including both HFE upramp and downramp, decreasing the downramp rate may mean 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.5.5. Channel Response to Flow Pulse in Western Grand Canyon

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. The Colorado River in Western Grand Canyon has significantly different morphology than that of the debris-fan dominated system upstream. Here, the morphology is characterized by tall eroding banks composed of delta and lake deposits from periods of much higher reservoir elevations in Lake Mead, and a shallow sand-bedded channel characterized by migrating sandbars. Studying how flow pulses affect bed-sediment dynamics in Western Grand Canyon is of importance for Hualapai commercial river operations, as shifting sandbars pose navigation challenges in Western Grand Canyon. 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 a 1- to 3-km long study reach near Columbine Falls at roughly RM 274. 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. Similar measurements were performed during the 2021 Spring Disturbance Flood and the 2023 Spring HFE, providing robust datasets for comparison.

Although annual monitoring of this reach is an unfunded component of Project B.2, data collection before and after a HFE will support future efforts to develop a sediment budget for this reach based on measured sand loads from the upstream on the Colorado River at Diamond Creek, estimates of sediment input from channel banks based on boat-based lidar measurements, and bedload measurements inferred from bedform tracking using sonar measurements. Understanding the causes and changes in the sediment budget of this reach will allow us to assess whether navigation challenges in Western Grand Canyon are increased by flow pulses.

Project Element B.5.6. Trout Management Flows

Trout Management Flows (TMFs) 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.

Outcomes and Products

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

- 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 response of sandbars to dam operations, 2020 to 2026.

Project Element B.2. Bathymetric and Topographic Mapping for Monitoring Sediment Storage and Riverbed Dynamics

- Report and maps for (data release) RM 0 to 32 (mapped in 2024).
- Report and maps for (data release) RM 166 to 225 (to be mapped in 2026). Reporting on this element may be delayed owing to reduced budget that may delay data processing.
- Report and/or journal article on geomorphic changes in Upper Marble Canyon and West-Central Grand Canyon describing effects of dam operations on sandbars and sand storage, 2013-2026.
- Journal article in collaboration with Project A comparing the results, with detailed error analysis, from the continuous mass-balance sand budgets under Project A with all topographic-based sand budgets to date measured by Project B.2
- Fact sheet for distribution to the general public providing a description of the purpose and key results of Project B.

Project Element B.3. Control Network and Survey Support

- Report summarizing the status of the control network.
- Data release that documents all control points in the current network and their uncertainties.
- Plan for migrating to use of the new spatial reference frames (NATRF2022) and maintaining the control network in the future.

Project Element B.4. Streamflow, Sediment, and Sandbar Modeling

- Communication of Sand Routing Model results and/or modeling support for HFE planning.
- Communication of Sandbar Model results to help GCDAMP evaluate proposed flow actions, including selecting between fall and spring HFE implementation under a one-year sediment accounting window.
- Improvements to the Sandbar model: 1) Improvements to the erosion model: report, journal publication, and/or code release anticipated in FY 2026. 2) Incorporating vegetation effects and multiple bar types: presentation of preliminary results in FY 2027.
- New two-dimensional streamflow model for RM 30 to RM 61. Report, journal publication, and/or code release anticipated in FY 2026.

- Fine Sediment Model (silt/clay and turbidity). Journal publication and code release anticipated in FY 2027.

Project Element B.5. Sandbar and Riverbed Response to Experimental Actions (to be funded only when experiments occur)

- Update on results of experimental action at annual reporting meeting.
- Data release for data collected for experimental project.
- Report or journal article describing field data and effects of experimental actions that occur.

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Budget

Fiscal Year 2025									
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
B.1. Sandbar and campsite monitoring with topographic surveys and remote cameras	$228,820	$2,000	$4,000	$27,391	$23,500	$0	$57,867	**$343,578**	
B.2. Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$355,170	$2,000	$2,000	$0	$18,800	$0	$78,863	**$456,833**	
B.3. Control network and survey support (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
B.4 Streamflow, sediment, and sandbar modeling (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project B	**$583,990**	**$4,000**	**$6,000**	**$27,391**	**$42,300**	**$0**	**$136,730**	**$800,410**	**$64,809**

Fiscal Year 2026									
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
B.1. Sandbar and campsite monitoring with topographic surveys and remote cameras	$262,687	$2,000	$4,000	$31,921	$23,500	$0	$68,642	**$392,751**	
B.2. Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$415,078	$2,000	$5,000	$86,680	$37,600	$0	$116,107	**$662,465**	
B.3. Control network and survey support (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
B.4 Streamflow, sediment, and sandbar modeling (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project B	**$677,764**	**$4,000**	**$9,000**	**$118,601**	**$61,100**	**$0**	**$184,750**	**$1,055,215**	**$85,767**

Fiscal Year 2027									
Project B Sandbar and Sediment Storage Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
B.1. Sandbar and campsite monitoring with topographic surveys and remote cameras	$275,431	$2,000	$4,000	$32,895	$23,500	$0	$74,257	**$412,083**	
B.2. Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$456,419	$2,000	$2,000	$0	$18,800	$0	$108,302	**$587,522**	
B.3. Control network and survey support (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
B.4 Streamflow, sediment, and sandbar modeling (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project B	**$731,850**	**$4,000**	**$6,000**	**$32,895**	**$42,300**	**$0**	**$182,559**	**$999,604**	**$83,393**

Budgets for Proposed Unfunded Project Elements

Fiscal Year 2025								
Project B	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 0.000%**	**Total**
B.3 Control Network and Survey Support	$129,645	$1,500	$15,000	$0	$0	$0	$31,860	$178,004
B.4 Streamflow Modeling	$110,606	$1,500	$0	$0	$0	$0	$24,439	$136,545

Fiscal Year 2026								
Project B	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 0.000%**	**Total**
B.3 Control Network and Survey Support	$137,989	$1,500	$15,000	$0	$0	$0	$34,915	$189,403
B.4 Streamflow Modeling	$113,423	$1,500	$0	$0	$0	$0	$25,973	$140,895

Fiscal Year 2027								
Project B	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 0.000%**	**Total**
B.3 Control Network and Survey Support	$146,881	$1,500	$15,000	$0	$0	$0	$38,231	$201,612
B.4 Streamflow Modeling	$143,702	$1,500	$0	$0	$0	$0	$33,977	$179,180

Project C: Riparian Vegetation Monitoring and Research

Investigators

Emily C. Palmquist[1], Brad Butterfield[2], David Dean[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Northern Arizona University, Department of Biological Sciences

Project Summary and Purpose

This project focuses on riparian plant communities, particularly how dam operations control plant composition and cover and how plant communities impact other valuable, managed resources. The proposed elements in this project address Goal 11 of Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) (U.S. Department of the Interior, 2016), LTEMP, which is related to maintaining diverse native riparian plant communities and quality wildlife habitat. Project Elements C.1 and C.4 additionally link to Goals 6 (Recreational Experience) and 7 (Sediment) by evaluating the complex linkages among plants, river flows, and sediment. Specifically, Project Element C.1 (**proposed as partially funded**) collects and summarizes annual monitoring data that identify if the LTEMP riparian vegetation goal is being met. A newly proposed aspect of this element aims to develop measures of wildlife habitat quality in collaboration with the Navajo Natural Heritage Program (NNHP). Project Element C.2 (**proposed as funded**) addresses the LTEMP riparian vegetation goal by experimentally evaluating plant physiological responses to steady vs. daily-fluctuating flows in the context of lower Lake Powell elevations. Project Element C.3 (**proposed as funded**) synthesizes data from Project Elements C.1 and C.2, as well as broad-scale regional datasets, to determine which dam-derived flows would be most likely to create plant communities that meet the characteristics desired in Goal 11. Project Element C.4 (**proposed as unfunded**) evaluates the impact of vegetation expansion on Colorado River channel change, including associating plant traits with sediment movement under different hydrological conditions, thus linking together a suite of LTEMP goals (Goals 2 Natural Processes, 6 Recreation, 7 Sediment, 11 Vegetation). Project Element C.5 (**proposed for experimental fund**) provides support for experimental vegetation management actions being implemented by Glen Canyon National Recreation Area and Grand Canyon National Park. Project Element C.6 (**proposed for experimental fund**) proposes to measure key physiological responses of plant species of interest during experimental flows. Project Element C.7 (**proposed for experimental fund**) proposes to evaluate how plant species with different physical traits alter flow velocity and sediment deposition during experimental flows.

The purpose of this project is to understand how dam operations are shaping riparian plant communities and associated resources (like sand) and determine if dam operations could be modified to align plant communities more closely to conditions listed in the LTEMP Goal 11 desired conditions. The proposed projects are designed to jointly address these topics by 1) assessing how current dam operations are changing plant communities, 2) identifying how the possible loss of daily fluctuating flows will impact plant communities, 3) evaluating what kinds of flow patterns are needed to promote desired communities, 4) determining if and how increased vegetation cover has changed river channel form, 5) providing research support to experimental management actions, 6) evaluating plant physiological response to experimental flow patterns, and 7) determining the impacts of common species on flow velocity and sediment deposition during flow experiments.

Hypotheses and Science Questions

The project aims to answer a suite of research questions that address the many ways dam operations and management actions influence plant communities and how plant communities, in turn, influence valuable resources in the CRe.

- 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 the historic high-water line of Lake Mead, approximately 240 river miles downstream of Lees Ferry?
- C.1 (Proposed Unfunded): Can bird habitat quality be reliably assessed by combining plant traits with estimates of plant species composition and cover? Can the data collected by the riparian plant monitoring program be used to assess patterns in riparian-dependent bird communities?
- C.2: Which plant species benefit or suffer from daily fluctuations?
- C.3: How do plant species interact with one another, and how are these interactions mediated by flow conditions? What are the implications of these interaction networks for vegetation responses to tamarisk die-off?
- C.3: What are the flow scenarios necessary to achieve specific vegetation objectives?
- C.4 (Proposed Unfunded): How has widespread vegetation expansion affected river channel form?
- C.4 (Proposed Unfunded): How effective are individual plant species at altering hydraulics and sediment transport?
- C.5 (Experimental Fund): How can experimental vegetation treatments being implemented by National Park Service (NPS) be improved upon?
- C.6 (Experimental Fund): What are the short-term physiological responses of common and uncommon riparian plant species to experimental flow patterns?

- C.7 (Experimental Fund): How do plants with differing physical traits alter flow velocity and sediment deposition during experimental flows?

Background

Riparian plant communities are an important resource in river ecosystems. Plants alter river geomorphology and sediment dynamics (Butterfield and others, 2020; Dean and Topping, 2024), support migratory and resident animals (Holmes and others, 2005b; Spence, 2006), provide traditional plant resources (Fairley, 2005; Jackson-Kelly and Hubbs, 2007), have positive and negative impacts on recreation (Stewart and others, 2003; Hadley and others, 2018;), increase regional biodiversity (Sabo and others, 2005), and mediate resources (like sand) between rivers and uplands (Sankey and others, 2023). Riparian plant communities and the services they provide can vary greatly depending on the flow and climate characteristics that shape the plant species that can establish and grow. In the Colorado River ecosystem between Glen Canyon Dam and Lake Mead (CRe), plant communities are inextricably linked to physical processes (sediment erosion, deposition, transport) and dependent biological communities (for example, birds) (Holmes and others, 2005b; Spence, 2006; Butterfield and others, 2020; Hazel and others, 2022; Sankey and others, 2023). The traits and life histories of the individual plant species that make up riparian plant communities determine the nature of sediment/plant interactions and the services or inconveniences provided to wildlife and recreationists.

Glen Canyon Dam operations control plant community composition and cover along the Colorado River in Glen, Marble, and Grand Canyons (Ralston and others, 2014; Sankey and others, 2015; Palmquist and others, 2023). Many aspects of Glen Canyon Dam derived flow patterns are likely drivers of riparian plant presence and abundance, such as increased base flows, reduction of peak flows (Sankey and others, 2015), daily fluctuating flows (Bejarano and others, 2018a), macroinvertebrate production flows (Gorla and others, 2015), summer and winter high discharge (Butterfield and others, 2023), and high flow experiments (Palmquist and others, 2023; Ralston, 2010). Flow patterns are layered on top of floristic differences along the river, such that plant communities in Glen Canyon, Marble Canyon, eastern Grand Canyon, and western Grand Canyon respond to dam operations in unique ways (Palmquist and others, 2023). Operational and experimental flows in the CRe have been designed for meeting water delivery agreements, producing power, promoting or hindering fish populations, redistributing sediment inputs, and stimulating macroinvertebrate production (Melis and others, 2016). Each of these flow patterns impacts riparian plant community resources by favoring some species over others. As dam operations are adaptively managed, flow patterns could be designed to support plant community goals.

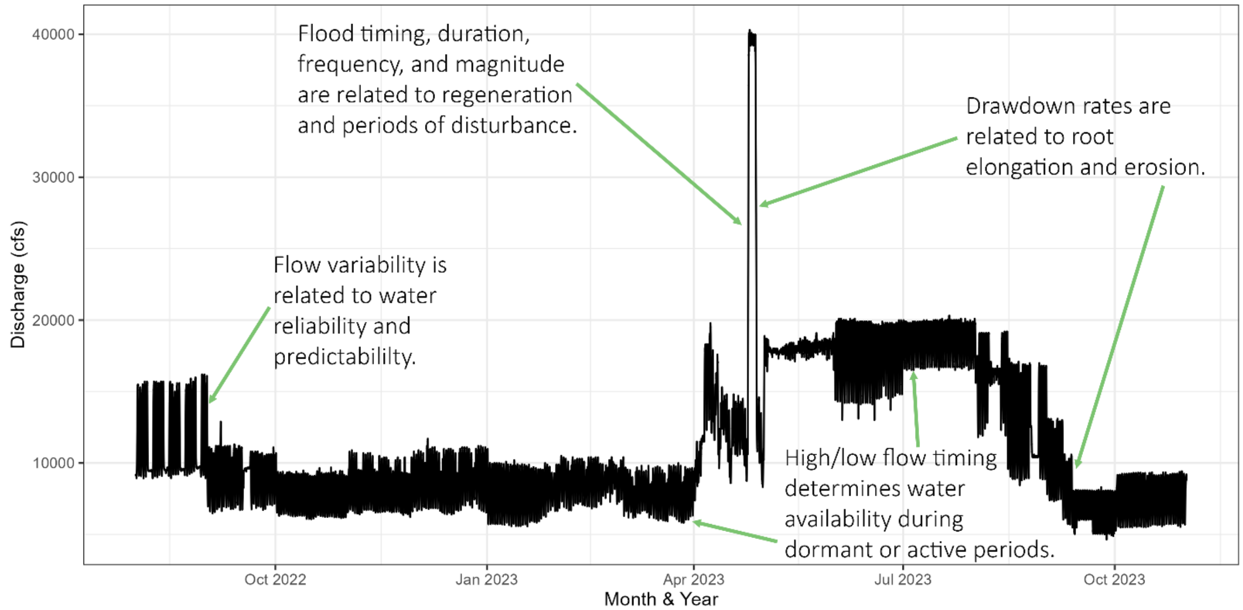

Figure 2. The instantaneous discharge record for water year 2023 (U.S. Geological Survey, 2024) illustrates the Glen Canyon Dam created flow patterns that are influencing riparian plant community cover and composition. Discharge is shown in cubic feet per second (cfs). Relevant aspects of the hydrograph are highlighted with green arrows and descriptive text.

Increases in riparian plant cover since Glen Canyon Dam operations began are very well documented (Turner and Karpiscak, 1980; Webb and others, 2011; Sankey and others, 2015). Impacts of operational adjustments on species composition have also been documented (Stevens and others, 1995; Stevens and Waring, 1986; Kearsley and Ayers, 1996; Ralston, 2010; Durning and others, 2021; Butterfield and others, 2023; Palmquist and others, 2023). These studies indicate that tamarisk (*Tamarix ramosissima* and hybrids with *T. chinensis*) established early, followed by *Salix exigua* (coyote willow). During the period with high fluctuating flows, riverine marshes formed and supported unique wetland communities (Stevens and others, 1995), which subsequently became drier and transitioned to woody species (Kearsley and Ayers, 1996). Recent plant expansion has been characterized by several native and nonnative species including *Pluchea sericea* (arrowweed), *Baccharis emoryi* (Emory's baccharis), *Phragmites australis* (common reed), and *Equisetum* x *ferrissii* (horsetail) (Durning and others, 2021; Palmquist and others, 2023). The current plant communities appear to have been strongly shaped by both patterns of inundation (Butterfield and Palmquist, 2023) and seasonality of high and low flow periods (Butterfield and others, 2023), such that changes to the frequency and magnitude of high flows and the timing of larger releases will change plant composition along the river. This information is largely based on field observations that are the result of the suite of flow patterns experienced within and across years. The majority of previous studies providing this information are based on field observations and are limited in their ability to tease apart the impacts of different aspects of the hydrograph and in the ability to forecast outside the range of previously experienced flows (unprecedented conditions).

Riparian plant communities, and the specific species within those communities, are increasingly being recognized as a driving force in sediment transport and geomorphological controls in the CRe (Hadley and others, 2018; Butterfield and others, 2020; Durning and others, 2021; Hazel and others, 2022; Sankey and others, 2023). Vegetation, sediment, and cultural resources are intimately linked through complex interactions and feedback loops (Butterfield and others, 2020; Kasprak and others, 2021; Merritt, 2022; Sankey and others, 2023). Riparian vegetation and cultural resources are dependent on river channel sediment deposits, and the condition of sediment and cultural resources are dependent on riparian vegetation growth and composition. The dam-related changes in plant communities across the CRe are substantive and have altered deposition and erosion in eddy sandbars (Butterfield and others, 2020), reduced windblow sand to uplands (Sankey and others, 2023), and decreased bare sand and campable area (Hadley and others, 2018; Durning and others, 2021; Kasprak and others, 2021). These changes may be large enough to have impacted the width of the Colorado River channel and shoreline complexity, similar to what has been documented in other southwestern river systems (Dean and Schmidt, 2011; Dean and Topping, 2019, 2024).

Ongoing climate change and aridification is leading to alterations in Glen Canyon Dam operations and other environmental variables, like air temperature, that shape the riparian communities of the CRe (Overpeck and Udall, 2020; Wheeler and others, 2022). The previous 60 years of dam operations has illustrated that the riparian plant communities of the CRe are dynamic and capable of rapid, significant change under altered hydrographs. The future conditions of the CRe based on operational changes and climate change will alter riparian plant communities and have cascading impacts on the CRe. The research presented in this project is aimed at tracking ongoing change, predicting future change, and understanding the impacts to other resources.

Proposed Work

Project Element C.1. Ground-based Riparian Vegetation Monitoring (proposed as partially funded)

Emily C. Palmquist[1], Brad Butterfield[2]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Northern Arizona University, Department of Biological Sciences

Monitoring the status and trends of native and nonnative plant species in the CRe provides the data for the LTEMP Goal 11 metrics: native species richness, ratio of native to nonnative species cover, and total native species cover. Annual measurement of plant species cover and composition will be characterized for (1) multiple geomorphic features representative of the CRe and (2) long-term monitoring sandbars and campsites surveyed as a part of Project B.

These data form the basis of plant community status and trends reporting and the underlying data for modeling efforts. Stratified-random sampling of multiple geomorphic features provides a thorough assessment of riparian plant composition, cover, richness, and native to nonnative species dominance on an annual basis throughout the CRe. Collecting data at long-term monitoring sandbars and campsites in conjunction with Project B provides a focused assessment of the impacts of plant communities on recreational resources and an opportunity for integration of vegetation and sediment dynamics.

Research Question C.1.1. 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 the Historic High-water Line of Lake Mead, Approximately 240 River Miles Downstream of Lees Ferry?

The monitoring protocol is described in detail in Palmquist and others (2018b) and monitoring results through 2019 are described in Palmquist and others (2023). The random sampling effort collects data annually at 80-100 sites between Glen Canyon Dam and river mile 240, where the influence of Lake Mead becomes apparent on the shorelines. As part of the experimental design, new sites are selected each year. This data set provides a full representation of the plant communities affected by Glen Canyon Dam. The long-term monitoring sandbar sites are 45 large sandbars that are sampled each year. These sites are not representative of the riparian communities across the entire CRe (Palmquist and others, 2023), but are important recreational sites and the sites used for evaluating the state of sand resources (Hazel and others, 2022). Data collection at the long-term monitoring sites is conducted in collaboration with Project B.1. The plant survey frames are included in the topographic survey, so that plant data can be closely linked to flow parameters and topographic change. Both survey efforts (random sampling and long-term monitoring sites) use ocular cover estimates of plant species rooted in 1-m^2 frames stratified by inundation frequency and geomorphic setting. Associated environmental data, such as height above minimum flows, ground cover, etc., are also collected. Previous research and monitoring illustrates that high and low flow patterns designed for other resources or for water delivery can have rapid impacts on plant communities that result in longer term patterns (Melis and others, 2011; Ralston, 2011). For example, the combination of the 2023 high flow experiment and high, consistent summer releases (Figure 1) reversed recent plant cover increases (Figure 2) (Palmquist and others, 2024), but this reversal could lead to a wide variety of plant community outcomes, including compositional shifts, rebounding plant growth, or sustained reduced cover in out years (Stevens and Waring, 1986; Stevens and Ayers, 1994; Melis and others, 2011; Ralston, 2011; Palmquist and others, 2023). To link specific flow patterns to changes in plant communities, data is needed from before the high flow experiment, shortly after flow patterns return to normal, and at least annually for several years after. Flow experiments and other flow anomalies occur every few years in this system, meaning that at least annual sampling is needed over time. As sampling frequency is reduced, it becomes progressively less clear what aspects of the hydrograph are causing observed change.

Thus, annual sampling of both randomly selected sites and the long-term monitoring sites is necessary to evaluate how flow experiments or operational anomalies (like equalization flows or smallmouth bass flows) affect plant communities and to evaluate long-term trends (Palmquist and others, 2023).

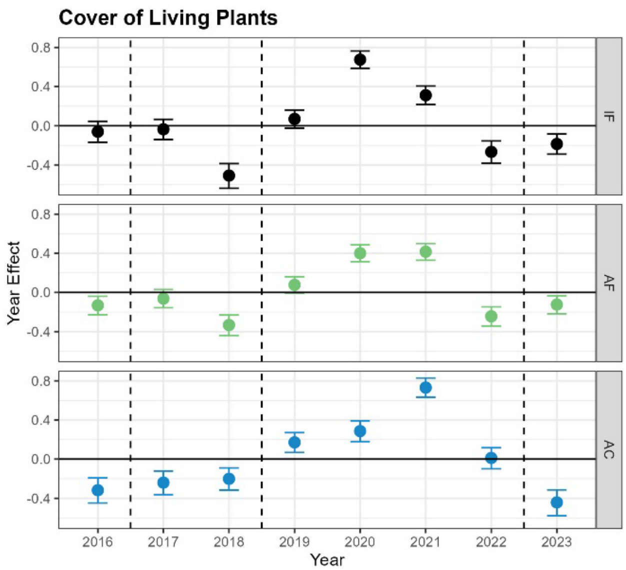

Figure 3. Mean and 95% credible intervals of year effects derived from modeling plant cover with a beta distribution in a Bayesian framework. Error bars that don't cross zero indicate significantly lower or higher values of the metric. Dotted lines indicate high flow experiments. Active channel: area inundated by flows between 8,000 and 25,000 cubic feet per second (cfs). Active floodplain: inundated by flows between 25,000 and 45,000 cfs. Inactive floodplain: inundated by flows over 45,000 cfs. Figure from Palmquist and others (2024).

Research Question C.1.2. Can Bird Habitat Quality be Reliably Assessed by Combining Plant Traits with Estimates of Plant Species Composition and Cover? Can the Data Collected by the Riparian Plant Monitoring Program be used to Assess Patterns in Riparian-dependent Bird Communities? (proposed as unfunded)

Maintaining wildlife habitat is explicitly stated in Goal 11, but evaluating wildlife habitat quality requires different vegetation assessments than are needed for determining the diversity and productivity of native plant species. A method for evaluating vegetation as wildlife habitat is needed if this part of the goal is to be assessed. Birds and bird habitat are of interest to Navajo stakeholders (Martin, 2009), is a primary consideration in other southwestern riparian areas (Grand and others, 2024), and has been assessed previously in the CRe (Holmes and others, 2005b). As noted in the previous CRe efforts, evaluating vegetation as wildlife habitat and assessing bird use of that habitat requires considerable effort (Holmes and others, 2005b; Spence, 2006). Rather than attempting long-term monitoring using the intensive methods used previously, the work proposed here aims to evaluate if current ongoing monitoring of plant composition and cover can be leveraged to evaluate bird habitat.

Plant guilds based on traits have been used elsewhere to assess how changes to hydrology can impact bird habitat (Merritt and Bateman, 2012) and recent studies have examined links between plant guilds and habitat characteristics (Cubley and others, 2020). It may be possible to combine the cover and composition data collected by ongoing monitoring efforts with plant trait data (plant height, specific leaf area, tissue density) (Lavorel and Garnier, 2002) to determine habitat suitability for different groups of birds. If these combined data sets (monitoring data and traits) are correlated with standard measures of bird habitat quality, all aspects of Goal 11 could be evaluated with no or very little extra monitoring.

In collaboration with the Navajo Nation Heritage Program (NNHP) Zoologist, the annual vegetation monitoring program will be leveraged to evaluate the quality of bird habitat currently supported by Glen Canyon Dam operations. This project will begin by evaluating methods previously used in the CRe and currently used along the lower Colorado River (Holmes and others, 2005a; Kearsley and others, 2006; Spence, 2006; Grand and others, 2024). Based on these traditional methods of measuring bird habitat suitability, we will develop comparable methods for measuring habitat suitability at our randomly selected monitoring sites. In FY 2025 and FY 2026, we will collect habitat structure data along with cover and composition data. The monitoring data from FY 2025 and FY 2026 will be transformed into estimates of suitable bird habitat using the existing plant trait data curated by the GCMRC riparian plant program (Palmquist and others, 2017). Combining the trait data with the cover and composition data will draw from other studies that use plant trait data in combination with habitat evaluation (Merritt and Bateman, 2012; Bateman and Merritt, 2020; Cubley and others, 2020) and concepts of effect traits used in the broader plant trait literature (Lavorel and Garnier, 2002; Kominoski and others, 2013). These estimates will then be compared to data generated by the traditional measures of habitat suitability. If the existing monitoring data provides similar estimates as the traditional measures, bird habitat suitability can be assessed using only the current monitoring protocol and associated trait data (Palmquist and others, 2017; Palmquist and others, 2018b).

As noted above, this effort will be conducted in collaboration with the NNHP. In conjunction with the habitat assessments, NNHP will develop methods to characterize bird communities in the CRe and will be funded through Project 5.P of the FY 2025-27 Reclamation Triennial Work Plan. The habitat and bird monitoring efforts will be coordinated such that the data can be analyzed jointly. The goals and methods of these efforts will be tailored to the needs of stakeholders from traditionally affiliated Tribal Nations, particularly Navajo Nation. There is intentional flexibility built into the above-mentioned data collection and analysis so that the methods can be adjusted and tailored to be responsive to Tribal values.

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

Brad Butterfield[1], Emily C. Palmquist[2]

[1]Northern Arizona University, Department of Biological Sciences
[2]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Research Question C.2.1. Which Plant Species Benefit or Suffer from Daily Fluctuations?

1) Daily fluctuating flows strongly influence the composition and functioning of riparian plant communities (Bejarano and others, 2018a). These fluctuations have certainly shaped the development of riparian plant communities in the CRe over the past 60 years (Sankey and others, 2015). Moving forward, unprecedented changes to Glen Canyon Dam operations – for example, dropping below power pool – could mean a dramatic shift in flow controls on the riparian plant community and subsequent opportunities to enhance the diversity and functioning of this important ecosystem.

2) Despite some long-term trends in the CRe, we have little direct evidence for how daily fluctuations have altered the riparian plant community. Most research on the effects of daily fluctuations comes from mesic watersheds in Europe, where contrasts between paired regulated and unregulated rivers have demonstrated general losses in species richness and functional redundancy under regulation (Aguiar and others, 2018; Bejarano and others, 2018b). Less is known about arid rivers. Numerous hydrophyllic species, particularly nonnative grasses (for example tall fescue, *Schedonorus arundinaceus*; Bermudagrass, *Cynodon dactylon*), are very abundant in parts of the CRe, and we hypothesize that this is due to pre-adaptations to fluctuating flows. Facultative riparian species that grow further above the channel, and therefore are not inundated by daily peak flows, such as arrowweed (*Pluchea sericea*), may also benefit by accessing soil moisture from those daily peaks (Gill and others, 2018; Palmquist and others, 2022; Butterfield and Palmquist, 2024). On the other hand, native riparian trees are largely absent from the CRe riparian zone, presumably due to regeneration requirements associated with natural flow regimes and minimal erosion (Mahoney and Rood, 1998; González and others, 2018). While based on multiple lines of indirect evidence, these predictions cannot be verified without controlled experiments.

3) We hypothesize that species vary significantly in their responses to hydropeaking, and that this variation is predictable based on plant functional traits related to seed and seedling ecology, clonality, and water use (Baladrón and others, 2023). We propose to test this hypothesis through a comprehensive assessment of plant responses to daily fluctuations across germination, establishment and growth, and including a functionally diverse suite of species.

4) We have conducted several experiments that inform the development of our daily fluctuation experimental design. First, from the perspective of experimental treatments, we conducted a pilot greenhouse experiment in the summer of 2023 to develop infrastructure for implementing daily fluctuations. We focused on just three species of interest and simulated (1) daily fluctuation treatments – none (control), daytime peak, and nighttime peak; and (2) hydrological zone treatments – near channel habitat (plant crown inundated at peak) and floodplain habitat (bottom of roots inundated at peak). We quantified three different metrics of plant performance and demonstrated physiologically relevant responses to the experimental treatments. Notably, species differed in their responses to treatments, indicating some species-specificity that could explain their responses to flow conditions in the CRe (Figure 3).

5) Two other studies have bearing on this proposal. First, we published a greenhouse experiment focusing on tolerance to persistent drought or flooding, in which we demonstrated significant correlations between species hydrological preferences in the field and their growth and physiological responses in the greenhouse (Butterfield and Palmquist, 2023). This study demonstrated the value of greenhouse experiments for predicting real-world flow responses and identified new root growth and stomatal conductance as valuable metrics of plant responses. Second, we published results from the spring disturbance flow that, while not representing daily fluctuations, did provide an opportunity to assess plant responses to short-term flow variation in the field (Butterfield and Palmquist, 2024). We found significant and biologically strong responses of plant water status to these short-term fluctuations that differed between species with different habitat preferences. In particular, we demonstrated the value of plant water potential measurements as a unique dimension of plant responses to short-term fluctuations. These two experiments provide an important foundation for both experimental design and plant responses – including new root growth, stomatal conductance, and stem water potential – as critical indicators of plant responses to short-term fluctuating flows.

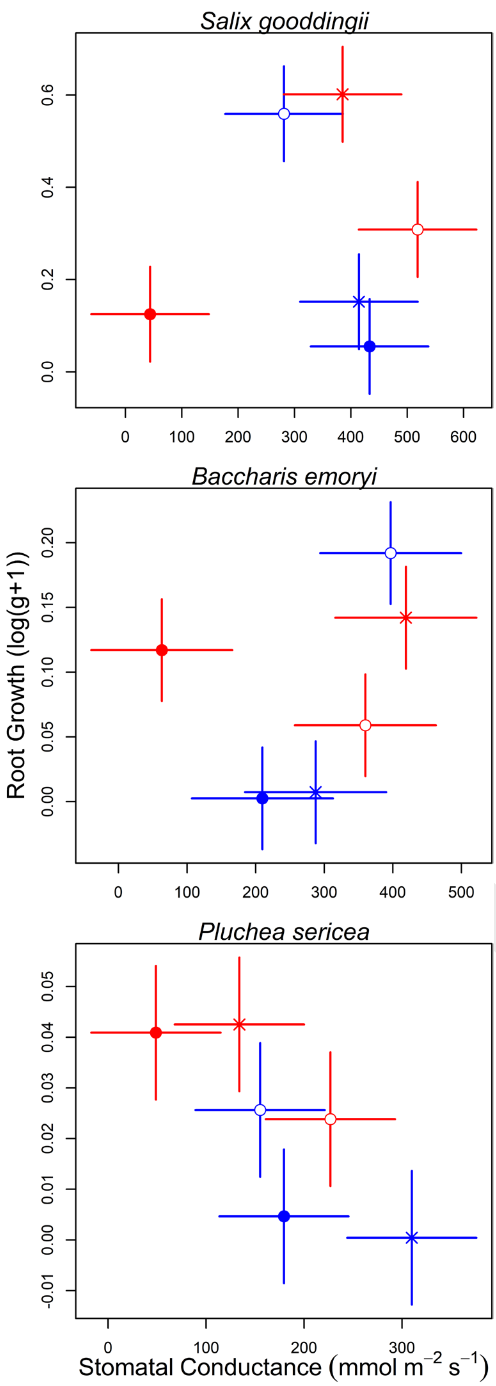

Figure 4. Results of pilot experiment testing the effects of daily fluctuations on performance three important CRe species; Gooding's willow (*Salix gooddingii*), Emory's baccharis (*Baccharis emoryi*), and arrowweed (*Pluchea sericea*). Blue symbols indicate plants where the crown was fully submerged during peak "flow", red symbols indicate plants with just the bottom of the pot submerged during peak flow. These treatments simulate near channel and floodplain habitats, respectively. Points are mean values, lines are 95% confidence intervals. Treatments include controls (x; no fluctuations), nighttime peaks (closed circle) and daytime peaks (open circle).

We intend to expand on the pilot greenhouse experiment in several ways. First, we will increase replication to improve statistical power to identify treatment effects. Second, we will increase the size of our experimental containers to simulate more realistic stage fluctuations. Third, we will assess multiple stages of plant demography, including germination, establishment, and growth. For the latter, we will utilize larger plants that allow us to make destructive measurements of leaf or stem water potentials without harming the plants, which was not feasible with the pilot experiment. In short, we propose to develop larger, more robust infrastructure for conducting daily fluctuation experiments that will be relevant to real-world conditions.

Methods

A. Infrastructure: We will establish infrastructure at the Northern Arizona University (NAU) Research Greenhouse Complex that will facilitate multiple experiments related to daily fluctuations. The primary components will be:

    1) Pairs of 1-m tall basins, each with a pond pump, connected by flexible tubing. This is a larger version of the setup we developed in 2023, in which one pump would turn on for a predetermined period of time at night, and the other 12 hours later during the day, in order to create symmetrical night/day peak flow conditions, analogous to the standing wave produced through the CRe by Glen Canyon Dam operations.

    2) A series of 1-m tall, 25 cm diameter PVC pipes, filled with sand and passively connected to the basins described above. As water levels move up and down in the basins, so too will the soil water levels in the pipes. The height of the containers will allow us to simulate more realistic stage changes than the smaller containers used in the pilot study.

    3) Pedestals will be used to adjust the base elevations of individual containers (Palmquist and others, 2022), simulating plants growing in near channel versus floodplain habitats.

B. Plant performance metrics: Following the review of Bejarano and others (2018a), we will test plant responses to fluctuations at multiple stages: reproduction, seedling establishment, and mature plant growth and physiology.

1) Reproduction: (Sexual) Seeds will be sown on the surface of containers. In treatments where the surface is not inundated by the daily peak, an initial watering event will be implemented to simulate rainfall or a high flow event (HFE). Germination timing and counts will be quantified. (Asexual) Plants will be propagated from seeds or cuttings in spring of 2025 in 30 cm tall, 8 cm diameter containers. In summer of 2026, the bottoms of the containers that plants are growing in will be removed, and the containers will be placed on top of the 25 cm diameter pipes filled with sand. Clonal growth will be measured as the number and biomass of new shoots growing out of the sand in the pipe, established via roots from the potted plant. This will simulate the ability of plants to spread clonally from higher elevations into the zone influenced by daily fluctuations near the river channel.
2) Establishment: Seeds will be germinated in germination chambers in the Butterfield Lab at NAU. Immediately upon root emergence, seedlings will be planted near the surface of containers. Seedling survival will be monitored frequently, and seedling growth, including maximum rooting depth, root biomass and aboveground biomass will be destructively measured after one month.
3) Growth and physiology: Plants will be propagated from seeds or cuttings in spring of 2025, and up-potted aggressively to maximize plant growth. This was a limitation of our pilot experiment, in that we were not able to establish large enough plants for frequent, semi-destructive measurements of plant water status in the small containers that we used. Plants will be subjected to flow fluctuation treatments in summer of 2027. Leaf and/or stem water potential and stomatal conductance will be monitored weekly, and photosynthetic rate will be monitored bi-weekly. All of the necessary equipment for these measurements is already available from the Butterfield and Palmquist labs. New root growth and plant height growth will be measured at the conclusion of the experiment. Carbon and nitrogen isotope ratios of leaves and roots, indicators of plant water stress, will be quantified at the Colorado Plateau Stable Isotope Laboratory at NAU.

C. Focal species: We will use results from a previous study on hydroclimate suitability (Butterfield and others, 2023) to select species for experimental treatments. Three categories of species will be selected: (1) those for which the CRe is predicted to be climatically suitable, and are abundant, (2) those for which the CRe is predicted to be climatically suitable, but are absent or rare, and (3) those for which the CRe is predicted to be climatically unsuitable but are abundant. Category 2 are species that are predicted to be negatively impacted by daily fluctuations, while Category 3 are species are that are predicted to benefit from daily fluctuations. Species from each category will be selected among plants with different growth forms (annuals, perennial grasses, sub-shrubs, shrubs, trees).

D. Analysis: Effects of experimental treatments will be quantified using general linear modeling approaches and used to quantify effect sizes of experimental treatments (for example, Butterfield and Palmquist, 2023). Functional traits for each species will be extracted from existing databases (Palmquist and others, 2017) and floras, and simplified via principal coordinates analyses. Trait components and the three species categories delineated in section C above will be used to predict treatment effect sizes among species. This framework can then be used to predict how other species not included in the experimental treatments are likely to be influenced by daily fluctuations. These results will then be incorporated into synthesis efforts outlined below.

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

Brad Butterfield[1], Emily C. Palmquist[2]

[1]Northern Arizona University, Department of Biological Sciences
[2]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

This project element will conduct forward-looking modeling efforts to identify the flow conditions that would optimize the vegetation objectives listed in Goal 11. Lags in vegetation responses to hydrological events and the lack of interannual flow variability in the CRe create the need to use data derived from regional collaborations and manipulative experiments that expand the range of biophysical parameters used to construct vegetation models. This project element will integrate ground-based vegetation monitoring (Project Element C.1), manipulative experiments (Project Element C.2), and existing regional data on riparian vegetation composition and hydrographs using advanced statistical modeling.

Research Question C.3.1. How do Plant Species Interact with one Another, and How Are These Interactions Mediated by Flow Conditions?

Plants interact with one another, and these interactions affect the relative abundance and dynamics of plant populations (Butterfield, 2009; Cavieres and others, 2014). Plants compete with one another for limiting resources such as water and light but can also facilitate one another through amelioration of environmental stressors like extreme temperatures or flood disturbance (Callaway, 2007). Environmental conditions strongly influence these interaction outcomes (Soliveres and Maestre, 2014), including in riparian zones, where multiple aspects of the flow regime can determine the intensity and outcome of plant-plant interactions.

Until now, our riparian vegetation models have assumed that plant species respond to flow conditions independently of one another. This was a simplifying assumption that helped us develop our first set of models, but we know that this ignores potentially important dynamics that influence vegetation status.

We hypothesize that certain species have outsized effects on the rest of the plant community, particularly arrowweed (*Pluchea sericea*) and tamarisk (*Tamarix ramosissima* and hybrids with *T. chinensis*). Tamarisk is particularly relevant, given the spread of the tamarisk beetle: as tamarisk stands die, other species may experience competitive release, while others that benefited from the deep shade and saline litter layer produced by tamarisk may suffer. We also expect that some other species may have strong competitive effects, such as the rapidly growing hydrophylic species like seepwillows (*Baccharis emoryi*, *Baccharis salicifolia*, *Baccharis sarothroides*) and clonal grasses. Less apparent interactions may also be occurring, particularly facilitative effects that buffer disturbances and promote vegetation encroachment. Indeed, we have demonstrated strong, flow-dependent effects of different plant functional groups on sedimentation (Butterfield and others, 2020), which can stabilize sediment that promotes the growth of other species.

We propose to quantify the interaction networks among riparian plant species within the CRe to achieve several inter-related objectives:

1) Identify how plant-plant interactions modify predictions of vegetation responses to flow conditions.
2) Determine how the balance between competition and facilitation may be influencing vegetation encroachment in different hydrological settings defined by the flow regime.
3) Predict the impacts of tamarisk mortality on subordinate species and vegetation metrics.

We will take advantage of recent developments in joint species distribution modeling (JSDMs) to identify associations between species that can be attributed to biotic interactions (competition or facilitation), and the hydrologic settings in which those interactions occur. This modeling effort will leverage the extensive ground-based monitoring data from C.1, an existing trait dataset that has been assembled for the CRe over multiple work plans (McCoy-Sulentic and others, 2017; Palmquist and others, 2017), and hydrological data from Project A.1 (U.S. Geological Survey, 2024).

We will implement JSDMs using the ‘boral’ package (Hui, 2016) in the R statistical platform. We will use elevation above critical hydrological thresholds – minimum of daily fluctuations, maximum of daily fluctuations, and HFEs (if present in a given time period) – as well as botanical region (Palmquist and others, 2018a) as environmental predictors. Functional traits will be used as covariates that mediate plant responses to the environmental variables. This has the effect of improving model predictions for species with lower frequency of occurrence, and improving generalization of model predictions based on trait-environment relationships that can be related to other taxa and communities.

After fitting the JSDMs, we will follow the workflow of D'Amen and others (2018) to identify residual variation in species covariances that can be attributed to competition and facilitation (Zurell and others, 2018). The hydrological preferences (Butterfield and others, 2023) of interacting species will then be used to identify the hydrological conditions that promote different types of interactions outcomes. These interactions will also be compared to the results of Butterfield and others (2020) to explore whether biotic interactions, particularly facilitation, is associated with species belonging to morphological functional groups related to sedimentation and, hence, positive feedbacks on sediment stabilization and plant encroachment. Finally, we will focus particularly on the strength and types of interactions associated with tamarisk and predict how tamarisk mortality is likely to influence vegetation composition in different hydrological settings.

Research Question C.3.2. What are the Flow Scenarios Necessary to Achieve Specific Vegetation Objectives?

This research question will conduct forward-looking modeling efforts to identify the flow conditions that would optimize the vegetation objectives listed in Goal 11. The metrics identified for Goal 11 will be used to frame the outcomes of this modeling. To date, our modeling efforts in the CRe have focused on the responses of riparian vegetation to flow patterns designed for other resources. While important, this approach does not provide a systematic assessment of how vegetation metrics respond to the full range of flow scenarios that could be implemented. Modeling a wider range of flow scenarios will provide a more comprehensive picture of the tradeoffs and compatibilities among different vegetation metrics and may also identify as-yet-unidentified dam operations that can satisfy multiple objectives.

We will combine our modeling innovations developed for the Colorado River Basin Post-2026 Operations Exploration Tool (WebTool, tool.crbpost2026dmdu.org) with synthetic models of plant responses to multiple hydrological dimensions. We developed an artificial environmental surface for the WebTool that facilitates rapid modeling of thousands of hydrological and climate scenarios while faithfully representing the riparian zone of the CRe (Yackulic and others, 2024). Specific hydrological variables and species-specific responses will include:

1) HFE magnitude. Species responses will be based on modeled results from our monitoring program, primarily the new JSDM response functions generated from addressing Research Question C.3.1 above.

2) HFE seasonality. Previous syntheses (Stromberg and others, 2007; Ralston and others, 2014) and case studies (Amlin and Rood, 2002) will be used to predict species responses to the seasonal timing of HFEs, primarily in the context of regeneration potential. Additional data on plant reproductive phenology will be extracted from floras and herbarium collections to further inform regeneration potential in response to HFE timing.

3) Base flow seasonality. Published models based on regional synthesis will be used to predict species responses to shifts in relative monthly volumes (Butterfield and others, 2023).

4) Magnitude of daily fluctuations. JSDM response functions described above, existing data on rooting depths (Stromberg, 2013; Palmquist and others, 2017), as well as experimental results from Project Element C.2, will be used to parameterize species responses to daily fluctuations.

Change in species-specific habitat suitability will be modeled in this four-dimensional hydrological space, with subsets selected for representation in 2-D and 3-D response surfaces. Species-specific responses will be aggregated to specific metrics of interest used in previous modeling efforts: total vegetation cover, species richness, and native dominance.

Project Element C.4. Biogeomorphic Linkages between Streamflow, Sediment Transport, and Vegetation Composition (proposed as unfunded)

David Dean[1], Emily C. Palmquist[1], Brad Butterfield[2], Joel Sankey[1], Paul Grams[1], Helen Fairley[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Northern Arizona University, Department of Biological Sciences

Traditional models describing drivers of physical river change typically relate the transport capacity of river's floods to the amount and size of sediment supplied to the river channel. If the floods are able to transport more sediment than is supplied to the channel, erosion will occur; if more sediment is supplied to the river channel than can be transported, deposition will occur (Lane, 1954). However, many studies have shown that those traditional models are overly simplistic because other phenomena, such as vegetation, can substantially modulate flow velocities, shear stress, sediment transport, and flood conveyance, thereby strongly influencing the size and shape of river channels and their floodplains (Figure 4) (Burkham, 1976a; Burkham, 1976b; Vincent and others, 2009; Nepf, 2012; Manners and others, 2014; Gellis and others, 2017; Dean and Topping, 2019, 2024; Walker and others, 2020). The effects of vegetation on hydraulics and sediment transport have been demonstrated in experimental flume studies (Tal and Paola, 2007; Zong and Nepf, 2010; Le Bouteiller and Venditti, 2014), numerical modeling studies (López and García, 1998; Griffin and others, 2005; Griffin and others, 2014), and large-scale field studies (Burkham, 1976b; Bywater-Reyes and others, 2017; Manners and others, 2013, 2014; Dean and Topping, 2019, 2024;). We refer to the effects of vegetation on channel morphology as *biogeomorphic* effects because that term highlights how biology (that is, vegetation) can influence geomorphic process and form.

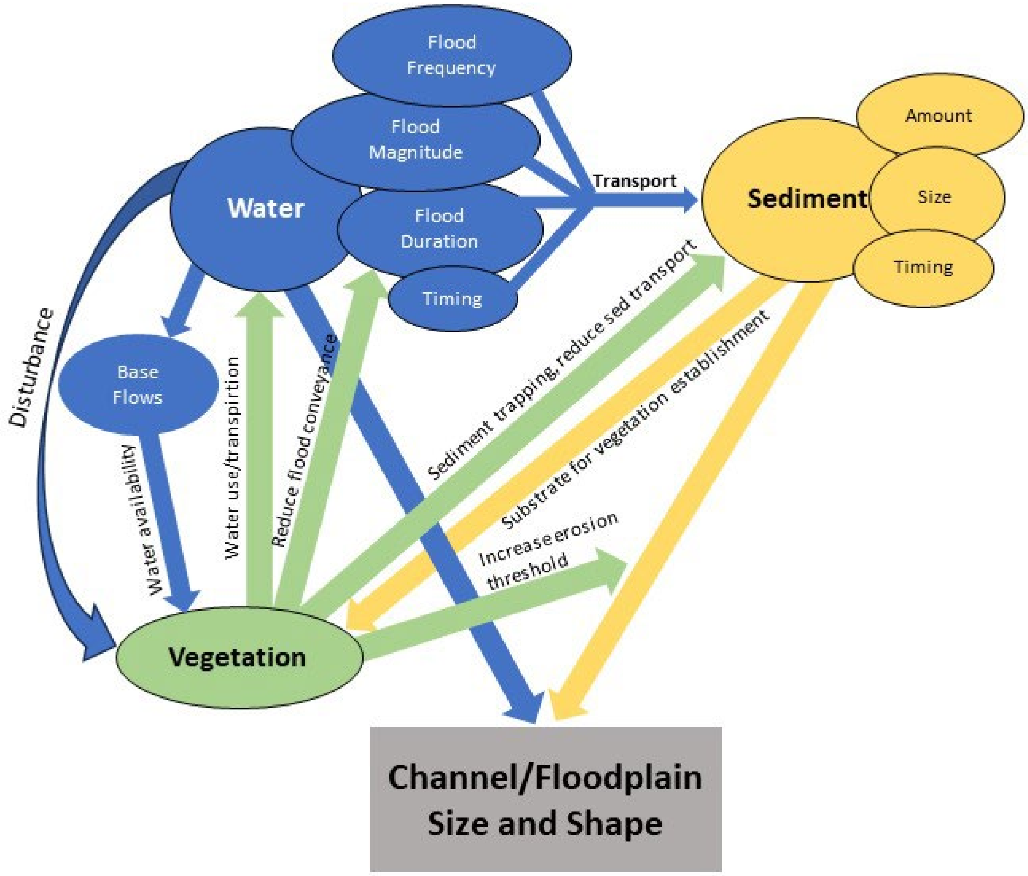

Figure 5. Diagram of the biogeomorphic feedbacks between river flow, sediment (also sed.), and vegetation. The size and shape of river channel and their floodplains is largely determined by the flood hydrology (flood magnitude, frequency, duration, and timing) and sediment supply (amount, size, and timing of delivery to the channel). The flood hydrology determines how much of the supplied sediment may be transported. Vegetation can substantially affect both hydrology and sediment transport because vegetation affects hydraulics, flood and sediment conveyance, and the erosional thresholds of the channel banks. Floods provide disturbance which may limit the establishment of vegetation and control where vegetation can establish. Sediment provides the substrate for which vegetation establishes on.

Thus, any large-scale change in vegetated area, species, or density may result in corresponding changes to river channels and their floodplains. The magnitude and style of channel and floodplain change driven by vegetation is dependent upon plant size, morphology, and density, with rigid, dense, multi-stemmed plants exerting a larger influence on geomorphic processes (Diehl and others, 2017; Manners and others, 2015; Bywater-Reyes and others, 2022).

Along the Colorado River in Marble and Grand Canyons, large increases in vegetated area, and large changes in species composition have occurred since the beginning of Glen Canyon Dam operations in 1963 (Sankey and others, 2015; McCoy-Sulentic and others, 2017; Durning and others, 2021) (Figure 5).

Sankey and others (2015) and Durning and others (2021) showed that the vegetated area throughout the river corridor expanded by 20% to almost 40%, with much of that expansion occurring through the establishment of relatively rigid, multi-stemmed, nonnative tamarisk and native seepwillow (*Baccharis* spp). Other plants that were largely responsible for the vegetation expansion were the shrub arrowweed (*Pluchea sericea*), and common reed (*Phragmites australis*). These native shrubs and common reed can grow in dense thickets along the channel margin and likely trap large amounts of sediment. Butterfield and others (2020) showed that deposition of sediment was correlated with vegetation presence and type along the Colorado River, with rhizomatous and herbaceous plants trapping sediment in eddy-separation zones, and tall herbaceous and large shrubs were effective at trapping sediment in eddy-reattachment zones.

Although Butterfield and others' (2020) work along the Colorado River in Marble and Grand Canyons shows that vegetation has trapped sediment in eddies downstream from debris fans, those results were found at select study sites and there have been no studies investigating whether system-wide changes in the channel of the Colorado River have occurred throughout the river corridor. We propose to conduct a multi-phased, interdisciplinary study aimed at quantifying system-wide changes to channel morphology relative to vegetation change. Project C.4.1 will build upon Butterfield and others (2020) and Durning and others (2021) by investigating whether large-scale changes in vegetated area and species have had a corresponding impact on river channel form. This will be done using a large suite of remote sensing data collected by Project L between 2002 and 2021. *Phase II* will use 2-dimensional hydraulic models to specifically analyze how effective individual vegetation species are at causing channel change by altering channel-margin/floodplain hydraulics and sediment transport. *Phase II* will build upon Butterfield and others (2020) and leverage hydraulic model development conducted in Project B.4. Both phases of work will provide needed information regarding vegetation management actions throughout the river corridor.

Figure 6. Matched photos from Sankey and others (2023) showing large expansion of riparian vegetation between 1923 (top) and 2019 (bottom) taken just upstream of President Harding Rapid. (Photo Credits. Top: E.C. La Rue, 1923, U.S. Geological Survey Photographic Library, Denver, CO. Bottom: A. H. Fairley, May 2019, U.S. Geological Survey)

Research Question C.4.1. How has Widespread Vegetation Expansion Affected River Channel Form? (proposed as unfunded)

C.4.1 is interdisciplinary, bridging work conducted by Project C and Project L. For this part of the project element, we will build on recent studies of vegetation change (Sankey and others, 2015; Durning and others, 2021) and biogeomorphic linkages demonstrated by Butterfield and others (2020) by conducting a system-wide analysis of historic channel changes relative to vegetation change. We will map the active channel boundaries visible in the 2002, 2009, 2013, and 2021 aerial imagery collected by Project L, and calculate changes in channel width over time; to date, there has been no large-scale analysis of channel width change along the Colorado River in Grand Canyon since the beginning of Glen Canyon Dam operations. Spatial changes in channel width will be correlated to changes in vegetated area, and species composition as mapped by Sankey and other (2015) and Durning and others (2021). Results of this study will illustrate: (a) where the largest changes in channel width have occurred, (b) whether changes in channel width are linked to an expansion of vegetation area, (c) and whether changes in width are specifically driven by specific vegetation species compositions.

Research Question C.4.2. How Effective are individual Plant Species at Altering Hydraulics and Sediment Transport? (proposed as unfunded)

C.4.2 of this study will bridge work done by both projects B and C. For this part of the project element, we will leverage 2-dimensional hydraulic modeling efforts in Marble Canyon conducted by Project B. We will use this model to determine the effects of specific plant species in causing changes to channel-margin and floodplain hydraulics and sediment transport, and thus also potential channel/floodplain change. The ability of vegetation to alter hydraulics and sediment transport is largely dependent upon plant morphology and flexibility; rigid, multi-stemmed plants have a larger effect on hydraulics and sediment transport than flexible, single-stemmed plants. Thus, to constrain the effects of individual species, we will measure plant traits in the field to determine plant frontal area (that is, the area of a plant that interacts with flow), plant flexibility, and buoyancy. These parameters will be used to develop depth-varied roughness curves for each measured species. These roughness curves will be input into the 2-dimensional hydraulic model, and simulations will be run to evaluate how patches of individual species along the channel margins affect flow velocity and shear stress distributions. We will also attempt to adapt these 2-dimensional models to run morphodynamic simulations to evaluate how these plant patches influence sediment deposition and erosion.

Project Element C.5. Experimental Vegetation Treatment Decision Support (proposed for Experimental Fund)

Emily C. Palmquist[1], Brad Butterfield[2]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Northern Arizona University, Department of Biological Sciences

The LTEMP identified the need for experimental vegetation management to be conducted in the CRe (U.S. Department of the Interior, 2016). These efforts are being led by Glen Canyon National Recreation Area and Grand Canyon National Park through Project 4.D of the FY 2025-27 Reclamation Triennial Work Plan (previously Project Elements C.7 and C.8 of the FY 2021-23 Reclamation Triennial Work Plan) and are monitored, in part, by Project D.3 of the FY 2025-27 GCMRC Triennial Work Plan. Thus far, the experimental vegetation treatments have focused on vegetation removal to support recreational and sociocultural resources but plans for revegetation with native species are included. These projects are collaborative in nature and explicitly state that planning, implementation, and evaluation of these projects will be coordinated among NPS, Tribal partners, and GCMRC.

This project element supports GCMRC Principal Investigator participation in regular meetings about site selection, monitoring, and experimental treatment plans. It also includes time for site visits, assistance with data analysis. We will collaborate on GCMRC Project D.3 and continue to facilitate NPS work as needed. Aspects of this support include, but are not limited to, assistance designing management experiments, consultation on plant species and collection locations for out-planting, sharing of data and maps, assistance with pre- and post-treatment data collection, facilitating the use of new restoration treatments and newly available research, site visits, input on the selection of work sites, and data analysis.

Project Element C.6. Plant Physiological Responses to Experimental Flows (proposed for Experimental Fund)

Periods of high and low flows are key drivers of riparian plant success (Tabacchi and others, 1998; Greet and others, 2011; Butterfield and others, 2023). Floods provide water to higher elevation plants but can also create plant stress through long periods of submergence. Periods of low flows can allow for plant establishment or desiccate species that rely on constant water supplies (most riparian species) (Mahoney and Rood, 1998; Stromberg and others, 2007). The timing, magnitude, and duration of high and low flow anomalies can result in stress-inducing conditions for some species while providing ideal conditions for others (Stromberg and others, 2007; Greet and others, 2013). Flow experiments designed to impact other CRe resources of concern (i.e., sediment deposition or nonnative fish expansion) will impact riparian plants through physiological stress in some species and physiological relief in others. Current monitoring methods cannot clearly disentangle the impacts of experimental flows from daily operations. The proposed experiments in C.2 provide an understanding of how plants respond to specific flow patterns in a greenhouse setting but are limited by the comparatively small plant size and age of plants used in the experiments and the climate conditions of the greenhouse (Palmquist and others, 2022; Butterfield and Palmquist, 2023). Collecting physiological measurements on plants before, during, and after planned flow experiments can help connect greenhouse experimental results to observed patterns of plant occurrence and cover in the field (Butterfield and Palmquist, 2024).

Physiological responses of plants during drawdowns and high flow releases can indicate if experimental flows benefit or disadvantage species of interest (Baladrón and others, 2022; Blasini and others, 2022; Butterfield and Palmquist, 2024; Moran and others, 2023). Measurements of photosynthesis, stomatal conductance, water potential, and leaf water content will be made on plants near Lees Ferry, AZ before, during, and after experimental flows to assess plant reactions to rapid changes in water levels. We conducted similar work during the Spring Disturbance Flow in 2020, resulting a in peer-reviewed publication and new insights into physiological responses of two important species to high and low flow anomalies (Butterfield and Palmquist, 2024).

Building off the results of this, other previous experiments (Palmquist and others, 2022; Butterfield and Palmquist, 2023), and Project Elements C.1 and C.2, physiological studies conducted during experimental flows will focus on species expected to be affected by the planned flow experiment and could include both native and nonnative species of interest, such as Emory's baccharis (*Baccharis emoryi*), coyote willow (*Salix exigua*), arrowweed (*Pluchea sericea*), tall fescue (*Schedonorus arundinaceus*), horsetail (*Equisetum* x*ferrissii*), common reed (*Phragmites australis*), honey mesquite (*Prosopis glandulosa*), salt cedar (*Tamarix* sp.), and species planted at Paria Beach (*Populus fremontii*, *Salix gooddingii*).

Project Element C.7. Effects of Plants on Flow Velocities and Sediment Transport During Experimental Flows (proposed for Experimental Fund)

Changes in river flows can result in a cascade of feedbacks between plant growth/expansion and associated changes in flow velocity and sediment transport. Changes in river flows alter riparian plant growth and expansion through the amount of water available for plant uptake and growth, increases in plant stress through prolonged submergence, seed dispersal, and erosion of suitable habitat. In turn, plant growth adds roughness to the channel banks which affects channel-margin flow velocities and sediment erosion and deposition, while plant loss has different impacts on channel shape and change. In many rivers, the expansion of riparian plants has resulted in large, and often irreversible, changes in river channel form (Vincent and others, 2009; Griffin and others, 2014; Manners and others, 2014; Dean and Topping, 2019, 2024).

In the CRe downstream from Glen Canyon Dam, there has been a widespread expansion of vegetation because of reduced flood disturbance and elevated baseflows. The species responsible for this expansion include nonnative tamarisk (rigid, multi-stemmed), native seepwillow (flexible, multistemmed), native arrowweed (flexible, multi-stemmed), and both native and nonnative common reed (dense, flexible, single-stemmed). Each of these species have complex relationships with flow velocity and sediment deposition that are impacting the CRe (Durning and others, 2021), and other plant species occurring along the river margin likely do, too. The magnitude by which vegetation can affect flow velocity and sediment transport is determined by stem density and morphology, which varies among species. In general, dense, rigid, multi-stemmed plants have a greater effect on flow velocity and sediment transport than sparse, flexible, single-stemmed plants. We plan to use the experimental fund to directly measure the effects of common plant species on flow velocities and sediment transport during experimental flows. During experimental flows, we will use an acoustic Doppler velocimeter to collect high-resolution 3-dimensional velocity and turbulence data within and adjacent to patches of different plant species to determine the magnitude that different species affect flow velocities. We will collect suspended-sediment samples upstream, within, and downstream of plant patches to determine the effects of plants on sediment transport.

Additionally, excavations will be made following experimental flows to determine the depth and grain size of sediment deposited within and adjacent to each plant patch. These data will help determine how different experimental flows may affect sediment deposition/erosion and therefore river channel form.

These data will also help environmental managers plan for restoration actions focused on riparian plant management, including plant removal.

Outcomes and Products

Project Element C.1. Ground-based Riparian Vegetation Monitoring (proposed as partially funded)

- Monitoring data collected annually FY 2025 through FY 2027 for both random sampling and long-term monitoring sandbars, properly archived, and used in other elements.
- Data summaries presented at GCMRC's Annual Reporting Meetings.
- Status and Trends presentation(s)/report describing long-term changes in plant communities.
- Publication on the ability to use ongoing monitoring data and plant trait data to assess wildlife habitat suitability **(Proposed Unfunded Component)**.

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

- Presentations of results at GCMRC's Annual Reporting Meetings.
- Journal publication on physiological responses of a suite of riparian plant species to daily fluctuating flows.

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

- Presentations of results at GCMRC's Annual Reporting Meetings.
- Journal publication on facilitation and competition among plant species in the CRe.
- Journal publication on dam operations that would best support plant community metrics for the CRe.

Project Element C.4. Biogeomorphic Linkages between Streamflow, Sediment Transport, and Vegetation Composition (proposed as unfunded)

- Maps of channel width change, released as a USGS Data Release.
- Summary of findings presented at GCMRC's Annual Reporting Meetings.
- Journal publication or USGS publication discussing role of vegetation in causing geomorphic change in the Colorado River in Marble and Grand Canyons.
- Journal publication or USGS publication discussing hydraulic effects of individual plant species.

Project Element C.5. Vegetation Management Decision Support (proposed for Experimental Fund)

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

Project Element C.6. Plant Physiological Responses to Experimental Flows (proposed for Experimental Fund)

- Summary of findings presented at GCMRC Annual Reporting Meeting.
- Data on plant species physiological responses to experimental flows, included in other plant response modeling (C.3).

Project Element C.7. Effects of Plants on Flow Velocities and Sediment Transport During Experimental Flows (proposed for Experimental Fund)

- Summary of findings presented at GCMRC Annual Reporting Meeting.
- Plant trait data added to published GCMRC plant trait data matrix (Palmquist and others, 2017).
- Data included in future modeling efforts on plant-sand interactions.

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Budget

Fiscal Year 2025									
Project C Riparian Vegetation Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
C.1. Ground-based riparian vegetation monitoring	$127,205	$3,615	$3,500	$80,293	$12,542	$0	$47,162	**$274,317**	
C.2. Determining hydrological tolerances and management tools for plant species of interest	$13,701	$0	$0	$0	$44,272	$0	$4,315	**$62,289**	
C.3. Predictive models and synthesis	$5,016	$0	$0	$0	$40,014	$0	$2,294	**$47,324**	
C.4. Biogeomorphic linkages between streamflow, sediment transport, and vegetation composition (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project C	**$145,922**	**$3,615**	**$3,500**	**$80,293**	**$96,828**	**$0**	**$53,771**	**$383,929**	**$24,336**

Fiscal Year 2026									
Project C Riparian Vegetation Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
C.1. Ground-based riparian vegetation monitoring	$136,109	$3,615	$3,500	$85,182	$13,327	$0	$52,020	**$293,753**	
C.2. Determining hydrological tolerances and management tools for plant species of interest	$15,197	$0	$0	$0	$48,681	$0	$4,895	**$68,773**	
C.3. Predictive models and synthesis	$10,735	$0	$0	$0	$48,846	$0	$3,891	**$63,472**	
C.4. Biogeomorphic linkages between streamflow, sediment transport, and vegetation composition (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project C	**$162,041**	**$3,615**	**$3,500**	**$85,182**	**$110,854**	**$0**	**$60,806**	**$425,998**	**$26,952**

Fiscal Year 2027									
Project C Riparian Vegetation Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
C.1. Ground-based riparian vegetation monitoring	$149,838	$1,615	$3,500	$88,103	$14,112	$0	$57,298	**$314,466**	
C.2. Determining hydrological tolerances and management tools for plant species of interest	$12,060	$0	$0	$0	$48,820	$0	$4,287	**$65,167**	
C.3. Predictive models and synthesis	$11,486	$0	$0	$0	$50,312	$0	$4,197	**$65,995**	
C.4. Biogeomorphic linkages between streamflow, sediment transport, and vegetation composition (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project C	**$173,384**	**$1,615**	**$3,500**	**$88,103**	**$113,244**	**$0**	**$65,782**	**$445,628**	**$28,697**

*GCDAMP Special Rate: Rate includes current DOI preferred rate (currently 15%; subject to change) and facilities rate (will vary annually). No USGS bureau overhead is charged (unique to the GCDAMP agreement).

**USGS Contributing Funds: The amount of funds required to cover the subsidy created by the reduced burden rate (i.e., GCDAMP Special Rate). As in previous years, SBSC/GCMRC will request these funds of the USGS cost-share program. These funds are not guaranteed.

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

Investigators

Joel B. Sankey[1], Helen Fairley[1], Joshua Caster[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Project Summary and Purpose

The Long-Term Experimental and Management Plan (LTEMP) (U.S. Department of the Interior, 2016a) goal for Archaeological and Cultural Resources is to maintain 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. In addition to these goals, the LTEMP acknowledges that the region "should not be conceptualized merely as multiple discrete or detached archeological sites, traditional cultural properties, and/or sacred places; but rather viewed as interconnected, culturally symbiotic areas of traditional religious and cultural value U.S. Department of the Interior, 2016a; page 1)."

Project D addresses the LTEMP goal by quantifying changes in the physical condition of river corridor archaeological sites in Grand Canyon and the associated surrounding landscape as a function of 1) dam operations, 2) experimental vegetation management, and 3) interacting natural processes and visitor impacts. While the dam and its operation are not the only sources of change affecting the CRe and associated archaeological sites, this project focuses on studying and monitoring dam effects and associated flow and non-flow experimental actions, in keeping with the mandates of the 1992 Grand Canyon Protection Act (GCPA; U.S. Department of the Interior, 1992) and consistent with the monitoring plan for cultural resources developed by GCMRC in 2015 and Reclamation's 2018 Historic Preservation Plan Bureau of Reclamation, 2018). The ongoing and experimental dam operations and vegetation management of interest are those that are undertaken under the Record of Decision (ROD) for the Glen Canyon Dam LTEMP final Environmental Impact Statement EIS; U.S. Department of the Interior, 2016b) through 2036. The experimental dam operations and experimental vegetation management are LTEMP flow actions and LTEMP non-flow actions, respectively, with the potential to influence the condition of the cultural landscape.

Three-quarters of the 362 river-corridor archaeological sites in Grand Canyon National Park (GRCA) depend on river-derived sand for their geomorphic context; this context, in turn supports native plant communities traditionally used by Indigenous peoples. The vast majority of cultural properties and associated contributing elements are now deprived of sand resupply in the modern, dam-controlled river system.

Sankey and others (2023) reported that most archaeological sites in GRCA along the Colorado River are eroding and are at increased environmental risk of erosion, from six decades of operations of Glen Canyon Dam. The proportion of sites affected by gullying processes controlled by the base-level of the Colorado River in Grand Canyon has increased since 2000 (Sankey and others, 2023). The wind-driven supply of river-derived sand, essential for covering sites, maintaining their geomorphic context, and helping to offset gully erosion has decreased for most archaeological sites since 1973 owing to effects of long-term dam operations on river sediment supply and invasive riparian vegetation expansion on sandbars (Sankey and others, 2023). These fundamental changes to landscape processes affecting archaeological site context and integrity, limit the ability of the National Park Service (NPS) to achieve environmental management goals to maintain or improve site integrity in-situ.

Archaeological site monitoring results illustrate some of the negative impacts of human river management and associated gully erosion on site condition and the physical integrity of prehistoric and historic archaeological sites. However, monitoring and research also demonstrate that windblown river sand can help to offset erosion impacts on archaeological site condition. Targeted riparian vegetation removal on sandbars may provide an environmental management opportunity to increase windblown sand supply from sandbars to archaeological sites, and thus increase in-situ preservation potential on a site-specific basis, while also helping to maintain the historic geomorphic context of these cultural resources and improve conditions for native, psammophilous (i.e., sand-loving) species. Effectiveness of vegetation management might theoretically be increased when coupled with HFEs to rebuild sandbars, or with periodic low river flows to expose sandbars, which in both cases are the sources of windblown sediment supply. In 2023, for the first time, experimental vegetation management and an HFE were implemented in combination in the same year in Grand Canyon. Without environmental management actions to increase in-situ preservation potential, sites along the Colorado River will likely continue to erode (Figure 1), leaving excavations or other mitigation of individual affected sites (e.g., Thorne, 1991), as the only options for preserving archaeological site information before it is lost, although this approach falls short of stated environmental-management goals and also conflicts with some tribal values.

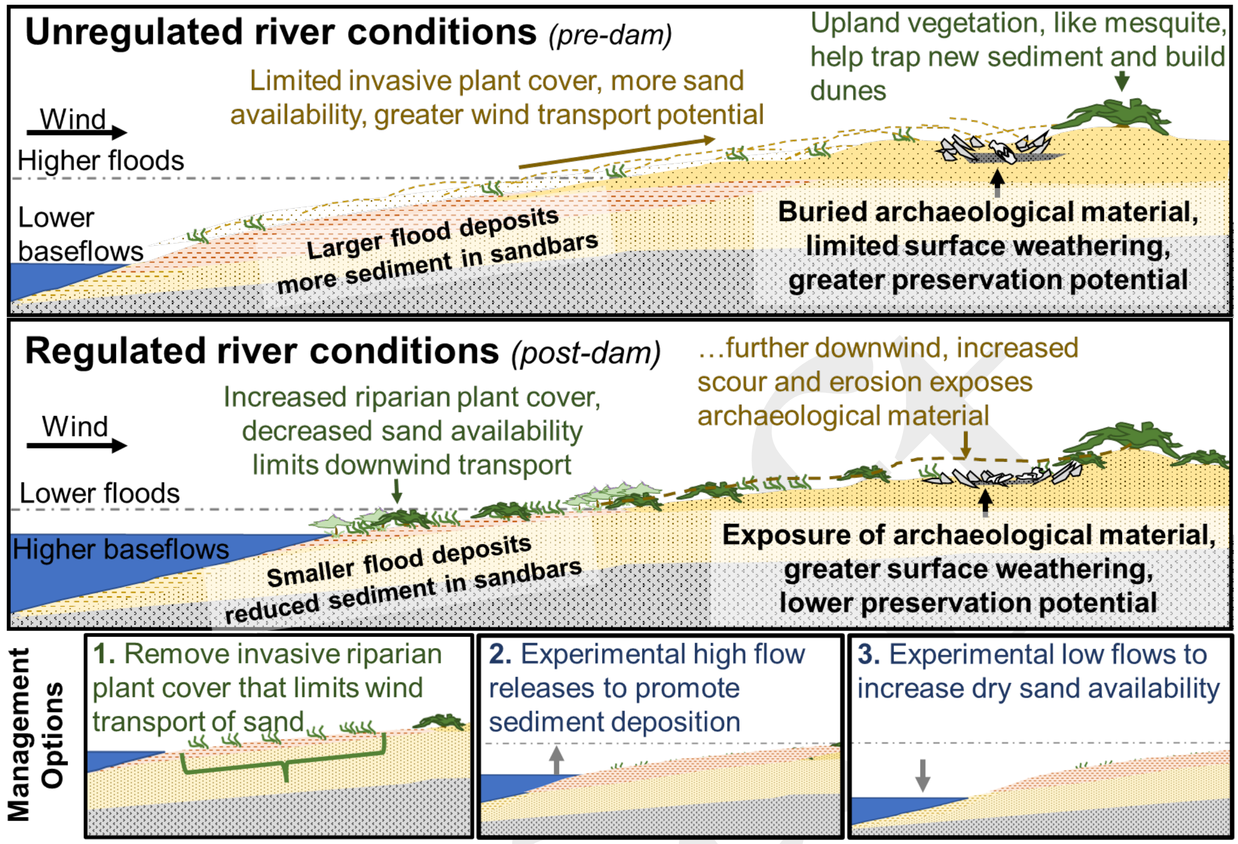

Figure 1. Illustration of effects of river regulation on archaeological sites that are located along the Colorado River downstream of Glen Canyon Dam in Grand Canyon National Park.

Science Questions

Project Element D.1. Monitoring the Effects Of Dam Operations on Archaeological Sites

Science Questions

- How do dam operations, HFEs and other LTEMP flow actions impact the LTEMP resource goal for cultural resources of preservation in place?

Hypotheses

- HFEs increase the resupply of river sand to archaeological sites in the river corridor and offset erosion, thus increasing the probability of achieving the LTEMP resource goal of preservation in place.
- 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.

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

Science 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 average annual flows?
- How has the distribution and abundance of plants of traditional importance to Native peoples of the Colorado Plateau changed over time, and specifically, how have they changed as a result of dam operations?
- How has the composition and density of riparian vegetation cover changed during the 50+ years since dam closure?
- Are specific 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?

Project Element D.3. Evaluating Effects of LTEMP Non-Flow Actions and other Experimental Vegetation Management on Archaeological Sites

Science Questions

- How do LTEMP non-flow actions – such as the experimental reduction of riparian vegetation growing on sandbars that blocks windblown transport of river sand – affect archaeological site preservation?
- Can improved experimental management actions not previously implemented in the current suite of LTEMP non-flow actions increase archaeological site preservation? For example, can actions based on different vegetation removal strategies, strategic plantings, and sediment capture using minimally invasive methods or traditional dryland farming knowledge and soil management practices of Hopi or other Indigenous people of the Grand Canyon region, improve archaeological site preservation?

Hypothesis

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

Project Element D.4. Pilot Study to Evaluate Potential to Extract Cultural and Ecological Information from Colorado River Deposits using eDNA, Phytoliths, and Pollen

Science Questions

- Can ancient eDNA be successfully extracted from pre-dam sedimentary deposits, and if so, what new or corroborating information can eDNA provide about the prehistoric and historic cultural landscape and terrestrial ecology of the pre-dam Colorado River corridor at various points in the past?
- How do the results of eDNA analysis of past environments in the CRe compare with, complement, or contradict information derived from analyzing just pollen or phytoliths from pre-dam sedimentary deposits of the same age?

Project Element D.5. Monitoring Petroglyphs and Pictographs with Photogrammetry And Lidar

Science Question

- Can repeat LiDAR scanning or photogrammetry at petroglyph or pictograph locations help to address concerns of individual Tribes and other signatories to the LTEMP Cultural Programmatic Agreement (PA) about the occurrence, rates, and causes of degradation of these sites?

Hypotheses

- Ground-based lidar surveys combined with photogrammetry provide sufficient detail to detect sub-centimeter changes in petroglyph and pictograph panel surfaces.
- Ground-based lidar, photogrammetry, or both improve documentation and analysis of pictograph panels, preserving baseline data for current and future monitoring programs.
- Pictograph form and compositional characteristics are detectable from ground-based lidar near-infrared reflectance.

Background

Significance and Justification

This project is designed to provide quantifiable information about the effects of Glen Canyon Dam on archaeological sites and other types of 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 to the LTEMP ROD (U.S. Department of the 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 D is designed to quantitatively evaluate that predicted outcome. Moreover, the LTEMP ROD recommends to "[e]xplore vegetation management to benefit high value recreational beaches and protect vulnerable archaeological sites." Project D is designed to quantitatively evaluate the outcome of ongoing vegetation management for archaeological sites.

In addition to being responsive to LTEMP goals and predictions, this project is responsive to multiple legal and regulatory mandates. The Grand Canyon Protection Act (U.S. Department of the 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 National Historic Preservation Act (NHPA; U.S. Congress, 1966) has somewhat similar obligations as GCPA (Bureau of Reclamation, 2017).

To fulfill its compliance obligations under the GCPA and specifically the NHPA, Reclamation has developed a Programmatic Agreement 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 D (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 & Management

More than two decades of research and monitoring in the CRe have demonstrated that throughout Grand Canyon, numerous archaeological sites and other cultural resources are subject to degradation from erosion processes and visitor impacts (East and others, 2016; U.S. Department of the Interior, 2016a; Cook and others, 2019; Sankey and others, 2023). Many of these sites occur in landforms, such as fluvial terraces, debris fans, and dunefields that are located above the elevations inundated by the contemporary dam-regulated river, yet the effects of dam operations have nonetheless accelerated and exacerbated rates of erosion affecting many of these sites (East and others, 2016; U.S. Department of the Interior, 2016a; East and others, 2017; Sankey and others, 2023). 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; Sankey and others, 2015; East and others, 2016; Kasprak and others, 2018; Sankey and others, 2018a).

In Grand Canyon National Park (GRCA), three-quarters of the 362 river-corridor archaeological sites depend on river-derived sand for their geomorphic context, and the vast majority of those sites are now deprived of sand resupply in the modern, dam-controlled river system. Sankey and others (2023) showed that most archaeological sites in GRCA along the Colorado River are eroding, and at increased environmental risk of erosion, from six decades of operations of Glen Canyon Dam. The wind-driven supply of river-derived sand, essential for maintaining site geomorphic context by covering sites and offsetting gully erosion, has decreased for most archaeological sites since 1973 owing to effects of long-term dam operations on river sediment supply and riparian vegetation expansion on sandbars (Sankey and others, 2023). The proportion of sites affected by gullying processes controlled by the local base-level of the Colorado River in Grand Canyon has increased since 2000 (Sankey and others, 2023). These fundamental changes to landscape processes affecting archaeological site context and integrity limit the ability of the National Park Service (NPS) to achieve environmental management goals to maintain or improve site integrity in-situ.

Archaeological site monitoring results illustrate some of the negative impacts of human river management and gully erosion on site condition and the physical integrity of prehistoric and historic archaeological sites (Sankey and others, 2023). However, targeted riparian vegetation removal on sandbars may provide an environmental management opportunity to increase windblown sand supply from sandbars to archaeological sites, and thus increase in-situ preservation potential on a site-specific basis (Pilkington and others, 2022; Sankey and others, 2023). The effectiveness of vegetation management can theoretically be increased when coupled with HFEs to rebuild sandbars, or with periodic low river flows to expose sandbars, which in both cases are the sources of windblown sediment supply (Sankey and others, 2018b; Sankey and others, 2022).

In 2023, for the first time, experimental vegetation management and an HFE were implemented in combination in the same year in Grand Canyon National Park. Without environmental management actions such as these to increase in-situ preservation potential, sites along the Colorado River will likely continue to erode, leaving excavations or other mitigation of individual affected sites (e.g., Thorne, 1991), as the only options for preserving archaeological site information before it is lost, although this approach falls short of stated environmental-management goals.

In Grand Canyon National Park and in Glen Canyon National Recreation Area, 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, pollen from cultigens; Fairley and others, 1994; Hereford and others, 1996; Fairley, 2003; Damp and others, 2007; 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 and other evidence of human activities (Collins and others, 2016; U.S. Department of the Interior, 2016a). 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 (Grams and others, 2007; U.S. Department of the Interior, 2016a). In other areas, sediment connectivity results from aeolian transport of sand from sandbars to dunefields located on terraces or debris fans (Draut and others, 2008; Draut and Rubin, 2008; Draut, 2012; East and others, 2016; U.S. Department of the Interior, 2016a; 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 (Sankey and others, 2014; Collins and others, 2016; U.S. Department of the Interior, 2016a; 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 EIS (U.S. Department of the 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 Alternative D, the alternative ultimately selected for implementation in the LTEMP ROD (U.S. Department of the Interior, 2016b), would result in modest benefits for cultural resources by improving sediment conditions that help to stabilize and preserve archaeological sites in situ, while also benefiting natural processes, campsites, riparian vegetation, hydropower, endangered fish, and other resources valued by society.

Over the past decade, GCMRC scientists have developed and refined methods for tracking trends and quantifying rates, amounts, and sources of geomorphic change affecting cultural resources in the CRe (Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016, 2017; Kasprak and others, 2017, 2018, 2021; Sankey and others, 2018a, b; Yackulic and others, 2024). These methods are well suited to evaluating whether the predictions of resource improvement in the LTEMP occur through 2036 (U.S. Department of the 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 Glen Canyon National Recreation Area (GLCA) reach, as being vulnerable to erosion and degradation from HFEs which are otherwise intended to distribute sediment throughout the Colorado River downstream of the Paria River (see also Grams and others, 2007). 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 the 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, GCMRC is providing science information used by NPS and tribal partners to manage 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 is well-suited for monitoring the vegetation management experiments and for quantifying the effectiveness of the treatments.

Proposed Work

Project Element D.1. Monitoring the Effects of Dam Operations on Archaeological Sites (modified ongoing study)

During FY 2025-27, GCMRC will continue long-term monitoring of archaeological sites using lidar to report on *LTEMP Cultural Resources Metric 1.2 Lidar Topographic Change Detection*. The purpose of this monitoring is to quantify the effects of dam operations and other factors on the geomorphic condition of a sample of archaeological sites in the Colorado River corridor in Grand Canyon National Park and Glen Canyon National Recreation Area that are within the area of potential effect of Glen Canyon Dam operations. Geomorphic changes are determined from ground-based lidar topographic surveys (also termed terrestrial laser scanning, TLS).

Lidar surveys use multiple scan positions placed outside of culturally sensitive areas to collect hundreds of millions of topographic measurements within and surrounding archaeological sites. These surveys are georeferenced to the established U.S. Geological Survey geodesic network and repeated at individual sites according to an established three-year rotational schedule (Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016, 2017; Sankey and others, 2018a, b, 2023; Caster and others, 2022). These repeated measurements are then used to calculate topographic changes resulting from erosion and deposition of river-sourced sediment (Figure 2). Identification of landscape change within a subset of archaeological sites are summarized, considering the timing and magnitude of changes to assess the influence of river and land management actions on potential changes in site conditions (Figure 2; Caster and others, 2022). The total sample size is 40 archaeological sites, with 12-14 sites monitored each year of the three-year work plan. The sample of 40 sites represents approximately 10% of the entire population of river corridor sites in Grand Canyon. We selected the sample of 40 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) positioned within the landscape to be resupplied with sand transferred by wind from adjacent sandbars. During the FY 2025-27 TWP, we will revisit all 40 sites at least once, 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 in Project Element D.3 below, to evaluate effects of experimental vegetation management implemented by NPS under the LTEMP.

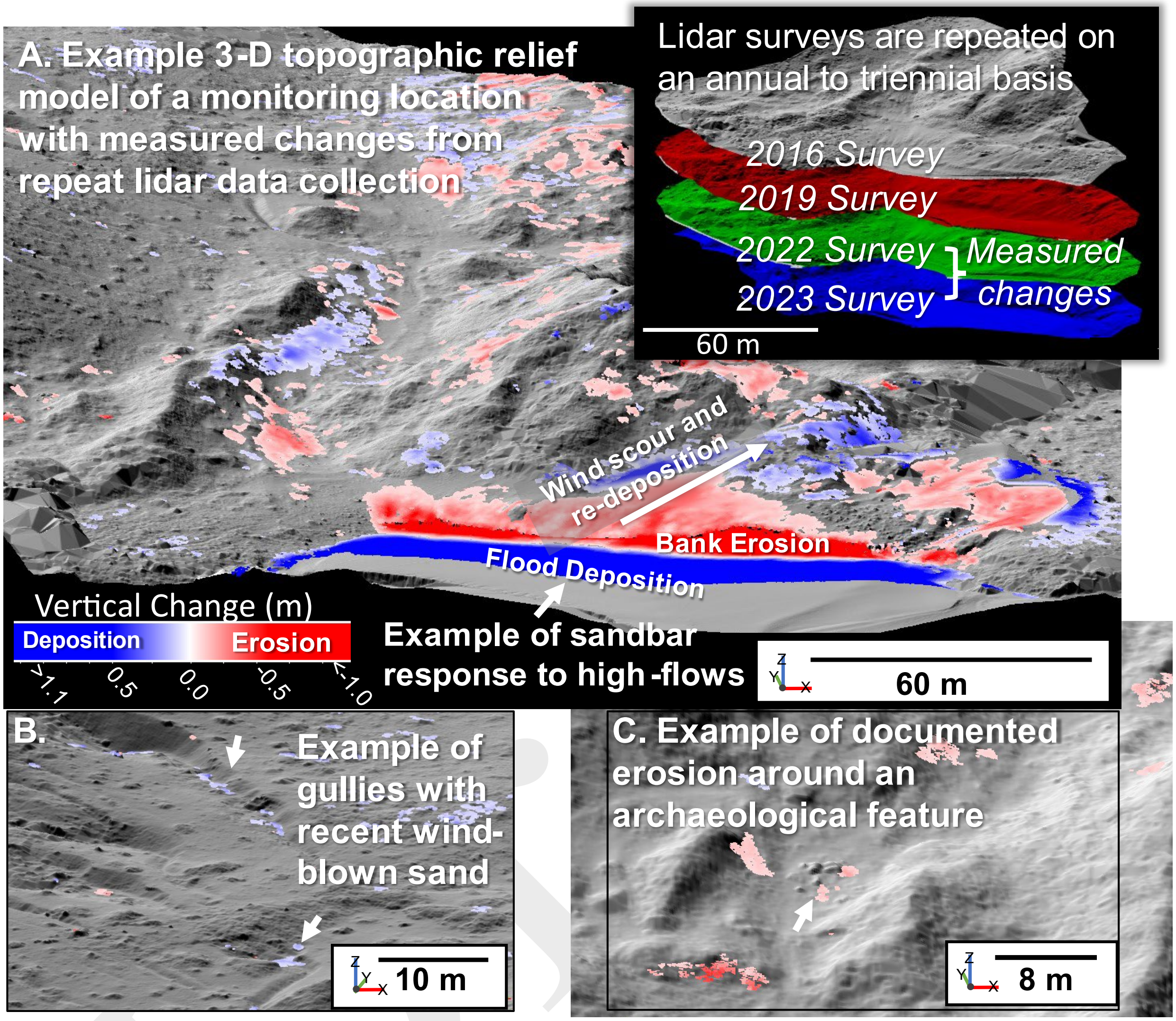

Figure 2. Example of repeat ground-based lidar and geomorphic change detection at a Grand Canyon National Park River Corridor monitoring location. A. 5-cm resolution topographic relief model with measured geomorphic changes (red = erosion; blue=deposition; gray = no significant change) between ground-based lidar surveys collected in April 2023 and May 2022. Labeled flood deposition and bank erosion represent significant geomorphic changes from the April 2023 High-Flow Experiment (HFE) conducted days before the 2023 survey. B. A subset of the 5-cm resolution topographic relief model with gully development demonstrating how wind-blown sand originating from upwind sandbars is partially ameliorating gully erosion through sand deposition. C. A subset of the 5-cm resolution topographic relief model with an archaeological feature. Ground-based lidar provides detailed measurements of archaeological components and repeat surveys permit assessment of changes in site and feature conditions.

There are three additional collaborative activities that this ongoing project element will contribute to. The first collaborative activity is that GCMRC and NPS will conduct an analysis of archaeological site monitoring data acquired by both agencies for sites within the area of potential effect of Glen Canyon Dam operations.

NPS reports on *LTEMP Cultural Resources Goal Metric 1.1 Site Integrity* through their projects 5.c and 5.d in the BOR TWP titled NPS Cultural Resource Monitoring – Grand Canyon and Glen Canyon, respectively.

USGS reports on *Metric 1.2 Lidar Topographic Change Detection* and *Metric 1.3 Fluvial Sediment Connectivity and Drainage Classifications*. Analysis will identify what the relationships are between the monitoring information acquired by NPS to determine site integrity and the data acquired by GCMRC to measure geomorphic and site classification changes. The second collaborative activity is that an interdisciplinary component of Project Element L.1, in collaboration with Projects B and D, will explore utility of existing remotely sensed data for measuring system-wide changes in high-elevation sand deposits. That interdisciplinary work will leverage the long-term lidar monitoring topographic change detection results acquired by Project Element D.1 as a basis for checking the accuracy of high elevation sand estimates using photogrammetric data. The third collaborative activity is that modeling efforts funded externally (i.e., not funded by the GCDAMP) through the USGS Mendenhall Post-doctoral Fellow program will model river sand transport and high-elevation sand deposition with specific consideration to archaeological site preservation potential. The Mendenhall program modeling project will leverage long-term monitoring data acquired by Project Element D.1.

Finally, during FY 2025-27, GCMRC Project Element D.1 will not monitor changes to archaeological site classifications to report on *LTEMP Cultural Resources Metric 1.3 Fluvial Sediment Connectivity and Drainage Classifications*; that metric is reported on an approximately decadal time interval and will be completed in a subsequent work plan.

Project Element D.2. Monitoring Landscape-Scale Ecosystem Change with Repeat Photography (continued ongoing study)

Repeat photography provides a powerful means of documenting and communicating ecological and geomorphic changes to landscapes over decadal timescales. It has been used for this purpose by scientists from a variety of disciplines for more than a century (Webb and others, 2010). In FY 2015-17, GCMRC initiated a pilot effort to monitor vegetation and geomorphic changes in the riparian zone using repeat photography. The initial results of this pilot photo-matching effort proved to be highly informative and useful for a variety of GCMRC projects: not only do the matched images visually document and illustrate dramatic changes in river corridor vegetation, they also document the ongoing loss of open sand areas throughout the river corridor as well as geomorphic changes to shorelines, campsites, and the river corridor as a whole (Figure 3; 4). This information is useful for reconstructing the pre-dam conditions under which archaeological sites and cultural landscapes existed prior to emplacement of Glen Canyon Dam. Furthermore, supplementary data that is being collected about the specific plant species within the modern photo views, compared to the historical views, provides a site-specific inventory of the plant species growing in the vicinity of archaeological sites today as compared to the past, which in turn informs us about the changing attributes of the cultural landscape in which the sites are embedded. This information also informs on the distribution and abundance of native plant species that are of traditional importance to the Indigenous peoples of the Colorado Plateau. Therefore, GCMRC has continued to acquire high-quality, high-resolution matches of historical imagery during subsequent years, relying heavily on volunteer labor and leveraging logistical support from Project Element D.1 to accomplish the field work, with post-field work photo-processing accomplished exclusively by volunteer labor.

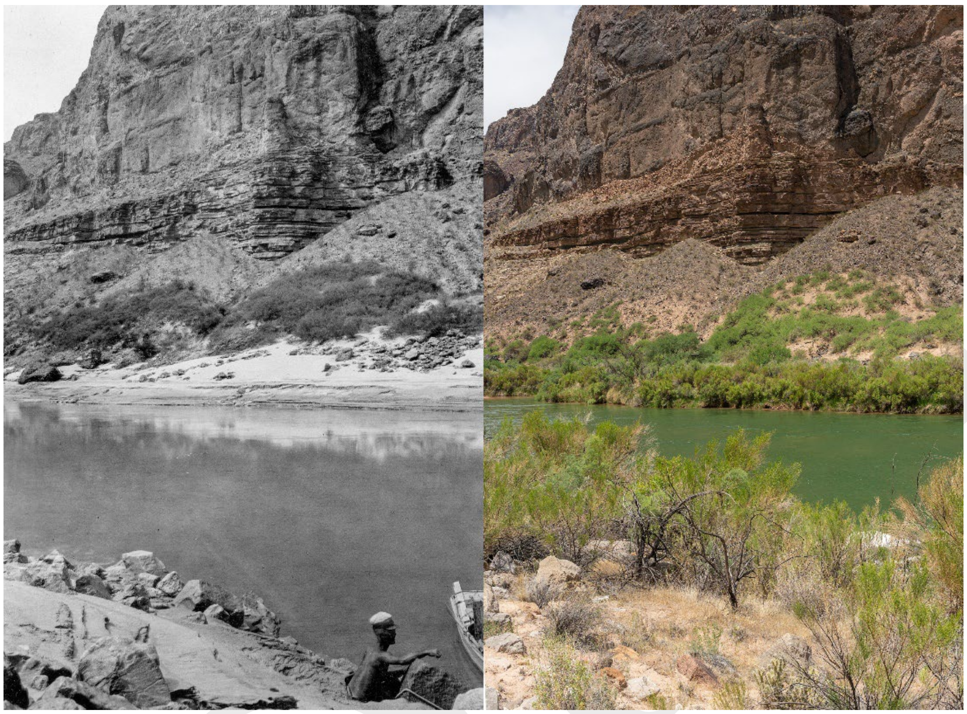

Figure 3. Example of a photo-match from 1923 (left) compared to 2021 (right). Note the wide, gently sloping, unvegetated sandy shoreline in 1923 compared to the nearly vertical, heavily vegetated shoreline in 2021. Also note significant thinning of the mesquite thicket above the pre-dam old high-water line. Stake No. 1157, River mile 179.8, taken from left bank, looking across and downstream to opposite shoreline. Left photo taken by E. C. LaRue September 18, 1923; right photo by A, H. Fairley, May 19, 2021.

During FY 2025-27, GCMRC will continue compiling a photographic record and associated database of ecological and geomorphic changes affecting the landscape and archaeological sites within the river corridor using well-established repeat photography methods (Turner and Karpisak, 1980; Webb, 1996, Webb and others, 2010, 2011; Scott and others, 2018.) To date, photo-matching efforts have focused on replicating photographs taken in 1923 during the USGS Birdseye Expedition (Boyer and Webb, 2007) and images taken 50 years later (in 1973) during an NPS-sponsored campsite inventory project (Weeden and others, 1975). We have also re-matched numerous photographs taken during the 1889-1890 Stanton expedition. Over the next three years, we plan to fill in temporal gaps in the photographic record, focusing initially on matching approximately 50 black-and-white images taken by Barry Goldwater during his 1940 river trip through Grand Canyon.

Another important photograph collection that we plan to match was compiled by Bill Belknap during a 1964 low-water trip through Grand Canyon. The Goldwater images will be valuable to match because they were taken by a highly skilled photographer following a period of lower flows and lower magnitude floods than the earlier Birdseye and Stanton images; therefore, they can provide a useful comparison of pre-dam riparian vegetation conditions closer to the time of dam construction and under somewhat different flow conditions compared to photographs from 1890 and 1923. The Belknap photos, also taken by a skilled photographer, provide a visual record of the river corridor immediately after the dam was completed, during exceptionally low water conditions. Neither the Goldwater images nor the Belknap images have been previously matched, to our knowledge.

Figure 4. Examples of vegetation encroachment on former campsites between 1973 and 2022. Top photos taken by unknown photographer in July 1973, bottom photos taken by A.H. Fairley in May 2022. Left photographs: Stake No. 5623, River Mile 170.5, left bank, looking upstream. Right photographs: Stake No. 5631, River Mile 185.1, left bank, looking upstream.

In FY 2025-27, we will continue to create high quality, accurate matches of these and other historical images to provide a high resolution, detailed visual record of decadal-scale ecosystem changes that can be used and analyzed by a variety of monitoring projects for years into the future. In addition to matching images, we will continue to collect detailed information on species-level vegetation change and geomorphic changes within each matched view.

As in the past, matching of these images will occur in conjunction with previously scheduled GCMRC research and monitoring trips and will be heavily reliant on volunteer labor to minimize project costs. After the image matches and vegetation and geomorphic data have been acquired, we will qualitatively and quantitatively analyze and ultimately publish the results of this work; we will also make the imagery available to stakeholders and the public through GCMRC's website.

Project Element D.3. Evaluating Effects of LTEMP Non-Flow Actions and other Experimental Vegetation Management on Archaeological Sites (modified ongoing study)

GCMRC will collaborate with NPS, the Hopi Tribe, and other interested parties, to study effects of experimental vegetation management, with a specific focus on LTEMP non-flow actions that may affect archaeological site preservation. There are three components proposed by GCMRC for this collaborative work.

The first component will continue evaluating effects of ongoing NPS experimental management at six pilot study sites where NPS removes invasive vegetation annually on river sandbars as an experimental LTEMP non-flow action (Pilkington and others, 2022; Sankey and others, 2023). GCMRC's research question is whether removal or reduction of riparian vegetation barriers located between river sandbars and archaeological sites can measurably increase the resupply of aeolian sediment to archaeological sites. The Lees Ferry Paria Beach restoration project and associated downwind archaeological sites will be added as a seventh monitoring location in FY 2025-27. We will evaluate this and subsequent components using ground-based lidar measurements from Project Element D.1. These measurements not only include detailed observations of the physical landscape, but also the biological landscape. We use iterative height filtering (Caster and others, 2022, 2024) to separate ground and vegetation measurements that permit evaluation of NPS treatments on the physical and biological environments (Figure 5; 6).

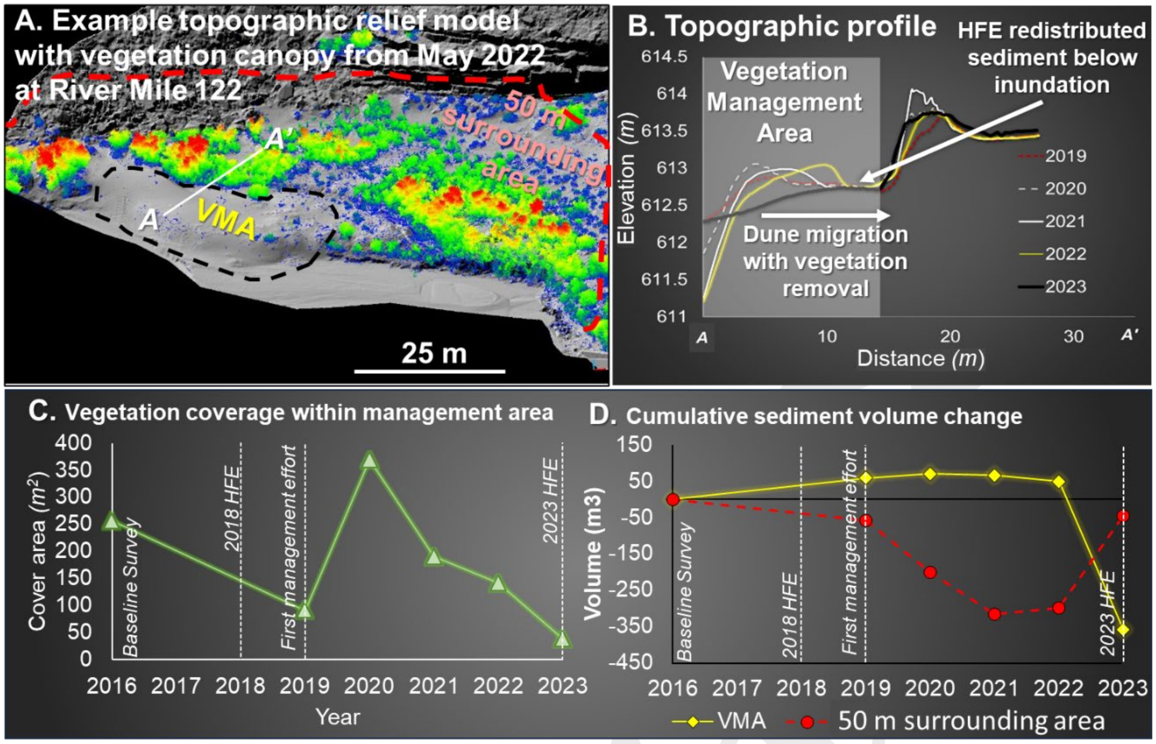

Figure 5. Example of a vegetation management site near river mile 122. A. 5-cm resolution topographic relief model (gray) with vegetation canopy height model (blue = <0.1m; green =<1m; red = >5m). The vegetation management area (VMA) and a 50 m buffer used for summarizing results (Panels C; D) are provided for reference. B. 2-D profile of line A-A' demonstrating dune crest movement during management actions. The topographic trends changed below the area of inundation with the most recent High-Flow Experiment (HFE; April 2023). C. Plot of changes in vegetation area within the VMA between 2016 (baseline year) and 2023 (most recent survey). Vegetation management efforts have been carried out almost annually since 2019. D. Plot of cumulative changes in sediment storage (net volume change) since 2016 for the VMA and the surrounding area, representing direct and downwind effects of vegetation management. Note that at this location, the most significant changes co-occurred with the 2023 high-flow experiment.

The second component will be to apply lessons learned during FY 2021-24 to propose and evaluate improved experimental management actions based on different vegetation removal strategies, strategic plantings, and sediment capture using minimally invasive methods. GCMRC seeks to collaborate with NPS, the Hopi Tribe, and other interested parties on this work. Specifically, through collaboration with the Hopi Tribe and others, we will explore the applicability of traditional dryland farming knowledge and soil management practices for achieving cultural resource preservation goals.

The third component will be to explore site restoration potential relative to degree of sandbar vegetation encroachment. The pilot sites evaluated (described in the first component above) are all associated with sandbars in early stages of vegetation encroachment. In FY 2025-27, we propose to evaluate additional study sites exhibiting much later vegetation encroachment stages to determine whether they can be effectively restored using similar experimental management techniques or whether different approaches to vegetation management may be warranted.

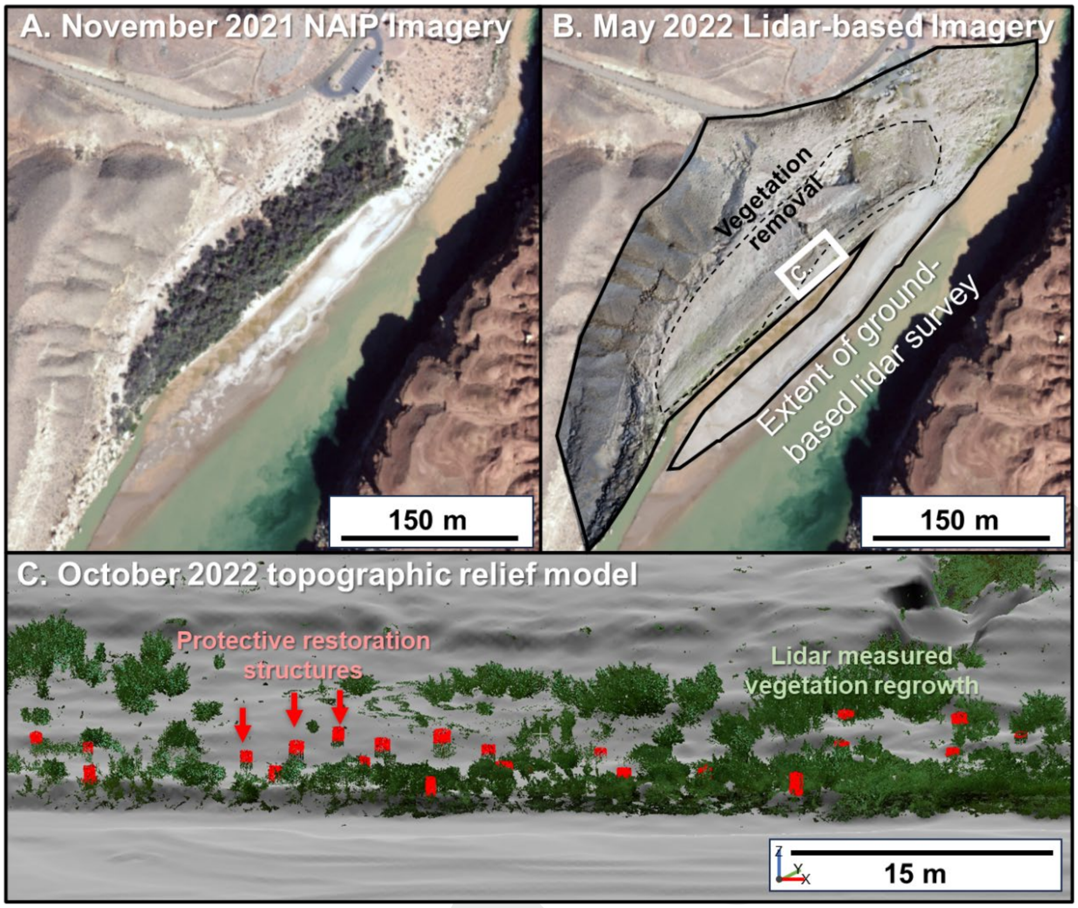

Figure 6. The Paria Beach restoration area. A. National agricultural imagery program (NAIP) aerial photography collected in November 2021 (courtesy of USGS). Note the dense woody vegetation near the center of the imagery. B. A partial "pseudo aerial imagery" dataset developed from photo colored ground-based lidar data collection overlaying the NAIP 2021 imagery. Note that during the May 2022 lidar survey, much of the woody vegetation had been removed. C. A portion of a 50-cm resolution topographic relief model from ground-based lidar collected in October 2022. Note that lidar measurements captured fencing installed to protect native plant restoration efforts as well as additional native and invasive plant re-establishment.

Note that in the FY 2021-24 work plan, the precedent to the collaborative work proposed above was supported by GCMRC Project D.1 to fund USGS efforts, and BOR Project C.7 to fund NPS efforts. For FY 2025-27, a similar funding strategy is proposed for USGS and NPS, but in this work plan, we (GCMRC) have broken out the vegetation management experimental study (this Project Element D.3) from the long-term monitoring Project Element (D.1) to clarify the different objectives involved with each study. For FY 2025-27 the related BOR TWP project is titled Project 4.d Experimental Vegetation Management – Grand Canyon.

Project Element D.4. Pilot Study to Evaluate Potential to Extract Cultural and Ecological Information from Colorado River Deposits using eDNA, Phytoliths, and Pollen (new study)

In the GCDAMP, past studies of the sediment resource have mainly focused on the physical dynamics of particles ranging in size from clay to boulders, with an emphasis on tracking the storage and redistribution of fine sediment (e.g., sand, silt and clay) within and immediately adjacent to the active river channel; however, the sediment resource is much more than just a physical attribute of the CRe. It also serves as a vehicle for nutrient cycling, provides a substrate for plants, influences the types and distribution of vegetation and wildlife habitat in the river corridor, and serves as a matrix for preserving archaeological sites *in situ*. In addition, the pre-dam Colorado River sediments are an untapped and largely unexplored repository of information about the pre-dam ecology and cultural history of the river corridor. Information embedded in pre-dam sedimentary deposits has the potential to inform on the characteristics and attributes of the prehistoric cultural landscapes which formed the original context for the hundreds of archaeological sites preserved in the river corridor today. This cultural landscape remains largely unstudied and undocumented, especially in terms of the prehistoric cultural activities and attributes that shaped the river corridor environment through time, including the agricultural fields and associated features that are believed to have been central aspects of the prehistoric cultural landscape in eastern and central Grand Canyon between ca. 3000 and 800 years ago.

In the past two decades, eDNA has become an increasingly important scientific tool for eliciting information about past and present environments and their associated biodiversity; indeed, according to some researchers, it has "revolutionized our knowledge of biogeography" (Pederson and others, 2015). While the methods and applications of eDNA research are continuing to evolve, ancient eDNA has already proved useful for documenting large-scale ecological changes associated with the Pleistocene-Holocene transition, including extending the persistence of certain species such as woolly mammoth in Alaska by several thousand years; documenting vegetation changes spanning 50,000 years; identifying the presence of rare, and in some cases, extinct species; and shedding additional light on many other topics pertaining to ancient environments and the archaeological record (Pederson and others, 2015).

In FY 2025-26, we propose to collaborate with the NPS and interested Tribes to undertake a pilot study to examine the types of environmental information that potentially can be extracted from pre-dam sedimentary deposits, with a focus on extracting ancient eDNA for the purpose of characterizing the prehistoric vegetation community and cultural landscape at various points in the past. In addition, we intend to use this pilot study to determine whether eDNA can be used to document the presence of ancient horticulture fields and identify specific cultigens that were grown in the river corridor in the past. Previous studies using standard palynological methods have produced evidence of maize agriculture possibly dating back more than 3,000 years ago; if this evidence can be substantiated through independent methods, such as eDNA, it would demonstrate that the Colorado River corridor in Grand Canyon contains some of the earliest evidence for maize horticulture anywhere on the Colorado Plateau. Other previous studies have produced evidence of cotton cultivation in association with ~1,000-year-old habitation sites, indicating that Grand Canyon may also have been one of the earliest sources for locally-grown cotton on the Colorado Plateau. Despite the pollen evidence, however, current knowledge of the extent and locations of past horticultural activity in the CRe is essentially non-existent. This study has the potential to illuminate several aspects of the archaeological and ecological record embedded within the pre-dam sedimentary deposits in Grand Canyon that have never been previously studied. To accomplish this pilot study, we propose to sample pre-dam river sediments at three locations in eastern Grand Canyon. These locations will be selected based on having appropriate characteristics for horticulture in the past and being most likely to preserve ancient eDNA, e.g., very fine-grained, water-laid sediments deposited preferably in an anaerobic environment without evidence of post-depositional disturbance. We propose to vertically core the selected deposits or if the deposits are exposed in profile, we will core them horizontally, following established protocols to minimize the possibility of contamination with modern DNA. We will collect several samples from each core. The cores will be sampled for eDNA as well as pollen and phytoliths, so that the results of all three methods can be compared and to ensure that we can recover environmental information from pollen and phytoliths, even if eDNA is not well-preserved. In addition, we will date the samples using either a radiocarbon dating method (if organic material is present in the sediment) or Optically Stimulated Luminescence (OSL).

Project Element D.5. Monitoring Petroglyphs And Pictographs with Photogrammetry and Lidar (new study)

In response to concerns by tribal members of the GCDAMP and at the request of the LTEMP Cultural Programmatic Agreement (PA) signatories, GCMRC will continue work to evaluate potential hazards to petroglyph and pictograph sites and collect data to monitor potential changes. An FY 2023 pilot study – which was unfunded, but GCMRC undertook at the request of the LTEMP Cultural PA – demonstrated the utility of photogrammetry and lidar for these purposes at a single petroglyph site (C:06:0005; “Supai Man”). Similar to Project Element D.1, this study used ground-based lidar, but collected measurements a finer resolution allowing for mm-scale characterization of the panel (Figure 7). Additionally, we used a Digital Single Lens Reflex (DSLR) camera to develop a true photogrammetric surface model (Figure 7) using Agisoft’s Metashape software. There are additional sites and structural remains for which these monitoring procedures could be applied throughout the Colorado River corridor.

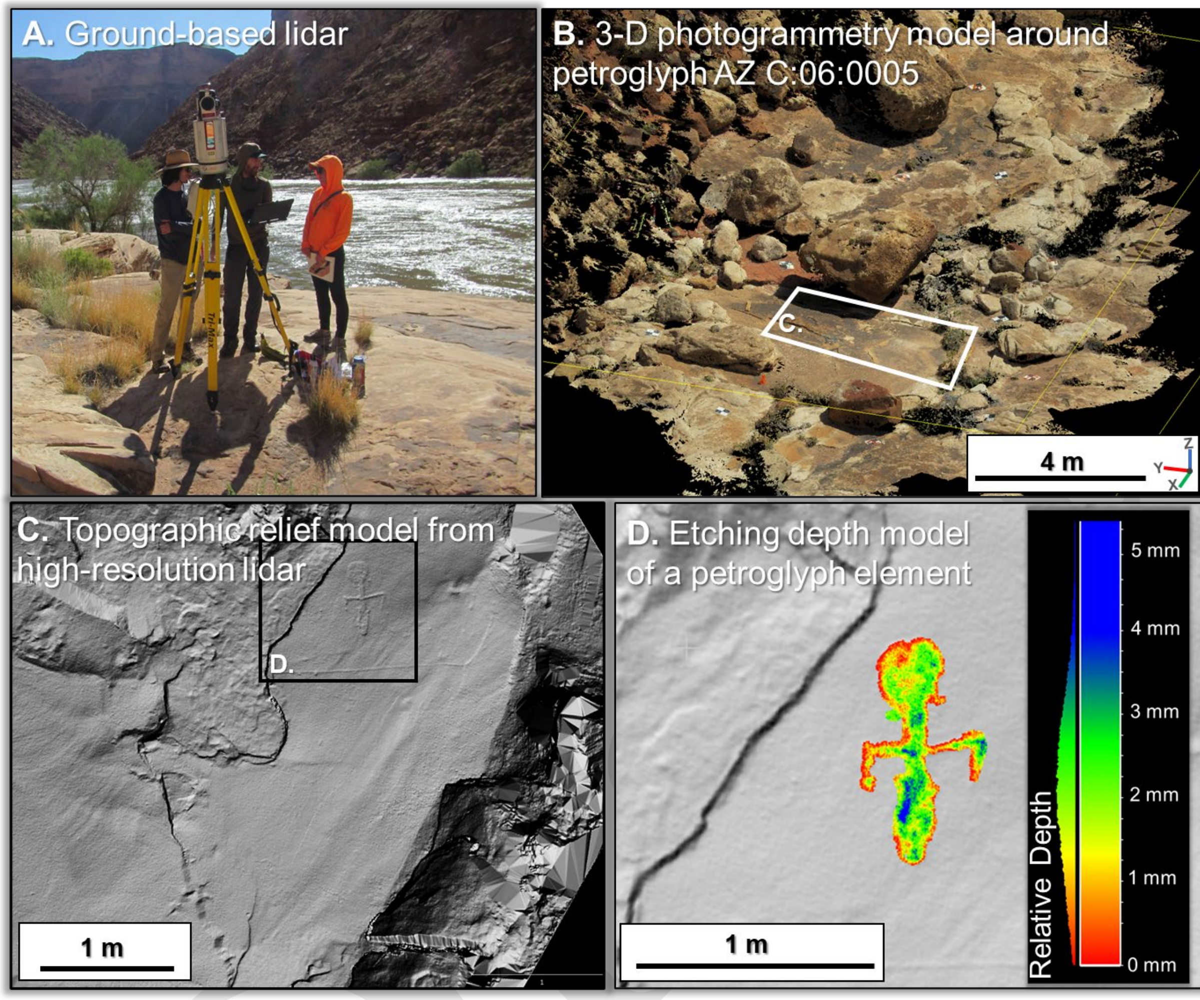

Figure 7. Pilot study data collected at the AZ C:06:0005 petroglyph site. A. Photograph of ground-based lidar collection by USGS scientists. B. Example of a true-color photogrammetry model that includes the petroglyph panel and surrounding area. C. 5-mm resolution topographic relief model of the petroglyph panel. D. Example of calculating estimated etching depth for a portion of the petroglyph panel derived from ground-based lidar.

To best meet the needs of tribal members of the GCDAMP and the LTEMP Cultural PA, this project element is designed to be responsive to identified priorities during FY 2025-27. During FY 2025, GCMRC will write a report detailing the 2023 findings from lidar monitoring at the petroglyph site C:06:0005. The initial results of this study demonstrated that such sites are vulnerable to a variety of hazards, including potential for direct effects of dam operations from inundation as well as indirect effects associated with visitor access and biochemical weathering. Collection of detailed monitoring records, as with the ground-based lidar and photogrammetry in this study, provides an important foundation for identifying hazards, providing a baseline condition assessment, and monitoring future changes in site condition.

During FY 2026, these detailed monitoring efforts will either be repeated at this site or conducted at other locations identified as priorities by LTEMP Cultural PA signatories.

For example, the NPS has identified several other petroglyph and pictograph sites in the river corridor that could benefit from more intensive monitoring using the above methods. In addition, several Tribes have expressed interest in possibly applying photogrammetry at other monitoring sites and were interested in learning more about the technical aspects of using these methods for monitoring purposes. At the LTEMP Cultural PA Meeting in March 2024, representatives from several tribes, including Hopi, Navajo, Southern Paiute Consortium, and Zuni, stated interest in creating learning opportunities with demonstrations of the photogrammetry and lidar monitoring methods at one or more petroglyph or pictograph sites of their choosing on their lands. As such, GCMRC proposes to work with each individual interested tribe to develop such a demonstration or workshop for tribal members to participate in and learn about collecting these types of data where there is interest in applying it within tribal monitoring programs.

Project Element D.6. Post-HFE Surveys (Experimental Fund request)

In each year that an HFE occurs, we will send one technician on a summer Grand Canyon Youth (GCY) trip to do additional post-HFE surveys, leveraging the field assistant support of the youths participating in trip. The technician will then process those data after returning from the trip, and the data will be added to the monitoring and research results reported by D.1 and D.3. This model for acquiring HFE-specific data that would otherwise not be acquired by Project D was successfully implemented as GCY trip project in June 2019 after the spring HFE that year.

Outcomes and Products

Project Element D.1 will produce:

- Annual presentations and reports on the status of the monitoring conducted under Project Element D.1. Submit to the GCDAMP at the end of Fiscal Years 2025, 2026, and 2027.

Project Element D.2 will produce:

- Annual summary of photographs matched each year.

Project Element D.3 will produce:

- Annual presentations and reports on the status of the monitoring conducted under Project Element D.3. Submit to the GCDAMP at the end of Fiscal Years 2025, 2026, and 2027.

Project Element D.4 will produce:

- (FY 2027) Presentation and report/journal article summarizing results of pilot project.

Project Element D.5 will produce:

- (FY 2025) Presentation and report on “Supai Man” (C:06:0005) pilot project results.

- (FY 2026 and FY 2027) hold a demonstration or workshop with each individual interested tribe on the photogrammetry and lidar methods for monitoring petroglyphs and pictographs.

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Budget

Fiscal Year 2025									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
D.1. Monitoring the effects of dam operations on archaeological sites	$121,118	$10,000	$20,000	$34,714	$0	$0	$40,511	**$226,343**	
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$7,138	$3,000	$2,500	$0	$0	$0	$2,755	**$15,393**	
D.3. Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$11,852	$9,000	$2,500	$12,268	$0	$0	$7,765	**$43,385**	
D.4. Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
D.5. Monitoring petroglyphs and pictographs with photogrammetry and lidar (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project D	**$140,108**	**$22,000**	**$25,000**	**$46,982**	**$0**	**$0**	**$51,032**	**$285,122**	**$24,415**

Fiscal Year 2026									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
D.1. Monitoring the effects of dam operations on archaeological sites	$192,081	$10,000	$20,000	$35,866	$0	$0	$58,296	**$316,243**	
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$22,914	$3,000	$1,000	$0	$0	$0	$6,082	**$32,996**	
D.3. Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$73,299	$9,000	$2,500	$12,699	$0	$0	$22,035	**$119,533**	
D.4. Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
D.5. Monitoring petroglyphs and pictographs with photogrammetry and lidar (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project D	**$288,294**	**$22,000**	**$23,500**	**$48,565**	**$0**	**$0**	**$86,413**	**$468,772**	**$40,518**

Fiscal Year 2027									
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**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
D.1. Monitoring the effects of dam operations on archaeological sites	$205,526	$10,000	$20,000	$37,030	$0	$0	$63,778	**$336,335**	
D.2. Monitoring landscape-scale ecosystem change with repeat photography	$24,518	$3,000	$1,000	$0	$0	$0	$6,673	**$35,191**	
D.3. Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$78,430	$9,000	$2,500	$0	$0	$0	$21,044	**$110,974**	
D.4. Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
D.5. Monitoring petroglyphs and pictographs with photogrammetry and lidar (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project D	**$308,474**	**$22,000**	**$23,500**	**$37,030**	**$0**	**$0**	**$91,495**	**$482,499**	**$42,087**

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

Investigators

Bridget Deemer[1], Ian Bishop[1], Charles B. Yackulic[1], Eric Scholl[1], Kimberly Dibble[1], Drew Eppehimer[1], Lindsay Hansen[1], Theodore Kennedy[1], Eric Frye[1], Tom Sabol[1], Robert Hall[2], Sasha Reed[3], Dan Buscombe[4], Mike Yard[5], Bob Tusso[1], David Topping[1], David Ward[6]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Flathead Lake Biological Station, University of Montana
[3]U.S. Geological Survey, Southwest Biological Science Center
[4]U.S. Geological Survey, Western Ecological Research Center, Santa Cruz, CA
[5]U.S. Geological Survey, *retired*
[6]U.S. Fish and Wildlife Service

Project Summary and Purpose

Ecosystem metabolism, or the rate of organic material fixation (accumulation) or depletion from an ecosystem, is key to understanding the energetic basis of food webs (Bernhardt and others, 2018; Rüegg and others, 2021). The two key components to riverine ecosystem metabolism are aquatic primary production and ecosystem respiration. Aquatic primary production, or the "green" food web, converts sunlight, carbon dioxide and water into simple carbohydrates via photosynthesis. Ecosystem respiration, or the "brown" food web, represents the decomposition and/or consumption of organic material by microbes, aquatic insects, fishes, or other animals. In the Colorado River downstream of Glen Canyon Dam (GCD), fishes are food limited (Cross and others, 2011) and energy (carbon) produced by autotrophs 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) "brown" carbon sources can also be an important driver of the food availability near tributary junctions and during flood pulses that occur during monsoon season (Cross and others, 2011; Wellard Kelly and others, 2013; Sabo and others, 2018). Rates of primary production (green food web) are an important control on flannelmouth sucker (*Catostomus latipinnis*) growth rates in Marble and Grand Canyon (Hansen and others, 2023a). While turbidity had a negative effect on flannelmouth sucker growth (Hansen and others, 2023a), initial findings from a similar model of humpback chub (*Gila cypha*) growth suggests turbidity has a positive association with growth, possibly indicating the role of the "brown" food web in fueling humpback chub growth (Hansen and others, *in prep*).

Phosphorus (P) is a key nutrient that can limit organismal growth and metabolic rates. Lake Powell retains disproportionately more P than other key nutrients like nitrogen and silica (Kelly, 2001), creating ecosystem P limitation (Gloss, 1977; Deemer and others, 2023b; Yard and others, 2023). We now have strong evidence of food web P limitation in Glen Canyon. P predicts rainbow trout (*Oncorhynchus mykiss*) 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 the Interior, 2016; Yackulic 2020). The density of aquatic insects in Glen Canyon are positively correlated with P availability at the annual scale (Korman and others, 2021), and bioenergetic modeling demonstrates that the Glen Canyon rainbow trout population is strongly regulated by rates of aquatic insect prey production, which is in turn controlled by P concentrations being released from the reservoir (Yard and others, 2023). In Marble and Grand Canyons, the relationship between P and ecosystem productivity is still emerging. Outside of periods when tributaries are flooding for extended periods, the availability of aquatic insect drift and the condition of native fishes are positively related to seasonal rates of gross primary production (GPP) near the Little Colorado River, highlighting the important role for aquatic primary production even 120 km downstream of the dam (Deemer, 2020). In dark sediment incubations conducted in both Glen Canyon and Grand Canyon, pH-mediated P release from sediments consistently led to increases in total protein production (Deemer and others, 2023b), suggesting that the “brown” food web is also limited by P.

Understanding the controls on Colorado River ecosystem production is an important step towards better managing the aquatic food base. For example, the canyon-wide increase in GPPGPP due to springtime low and steady weekend bug flows (Deemer and others, 2022) was estimated to increase rates of flannelmouth sucker growth by 1.6 mm per month, or approximately the same effect as warming the river by 1.1 °C (Hansen and others, 2023a), demonstrating a measurable link between a dam management strategy and native fish populations. During 2022 and 2023, the river has experienced unprecedented water quality conditions (U.S. Geological Survey, 2024), further underscoring the need to understand how abiotic factors interact to affect the base of the food web. The role of temperature verses other abiotic factors as controls on ecosystem metabolic rates is a key question in ecology (Bernhardt and others, 2018; Battin and others, 2023) and considerable uncertainty exists regarding how the green and brown food web in Grand Canyon will respond to temperature change. In Glen Canyon, P may limit decomposition rates even as waters warm (Scholl and others, 2024). While rates of primary production during clear water conditions appear to scale with river water temperatures at some locations and times, this relationship sometimes falls apart suggesting other factors may control primary productivity, with P limitation a leading candidate (U.S. Geological Survey, 2024). Dramatic temperature changes may also cause shifts in structure of primary producer communities, changing the availability of the most preferential species and the persistence of nuisance taxa. These changes in the food web are expected to interact with direct impacts of temperature, and other environmental drivers, on fish metabolism and other aspects of fish biology to determine the overall impact of environmental drivers on fish population dynamics. Overall, Project E is designed to capture and link changes in primary productivity, decomposition, and the community composition of primary producers to changes in bottom-up drivers such as light, temperature, flow, and nutrients and to further develop links between these bottom-up drivers and higher trophic levels.

In the FY 2025-27 Glen Canyon Dam Adaptive Management Program (GCDAMP) Triennial Work Plan (TWP), we propose to revise three elements from the FY 2021-23 GCDAMP TWP (Project Elements E.1, E.2, and E.4) and add a new element that focuses on ecosystem metabolism in the Western Grand Canyon (E.3). Several sub-elements propose to analyze data collected during the last work plan (mass balance P budgeting in E.1; vegetation mapping in Glen Canyon and GPP modeling exercises in E.2; bioenergetics modeling in E.4). Several new sub-elements propose to explore P uptake by primary producers during turbid, high P conditions (E.1), to survey benthic diatom populations in Grand Canyon and establish a modern molecular baseline for their abundance and distribution (E.2), and to examine the role of litter decomposition in the Western Grand Canyon food web (E.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.

Project 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: Interannual differences in tributary sourced P are much larger than interannual differences in P loading from Glen Canyon Dam.
- H3: Benthic primary producers capture and store significant quantities of storm-supplied P.
- H4: Storm-driven P mobilization from the Little Colorado River can fertilize a substantial portion of the mainstem river due to the timescale of P desorption kinetics.

Project Element E.2.

- H5: Phosphorus is more limiting to GPP in the spring than during other seasons. The degree of phosphorus limitation also varies spatially, with Glen and Marble Canyon being especially P limited.

- H6: GPP seasonality in Glen Canyon is driven by the distinct environmental preferences/tolerances of algal and macrophytic producers.
- H7: Shifts in Lake Powell plankton entrainment, rooted macrophytes, and macroalgal species within Glen Canyon correspond to changes in dam operations (e.g., high flow events) and changes to reservoir elevation.
- H8: Declining reservoir elevations and associated changing GCD outflow water quality negatively impacts the preferred food base (benthic diatom community) composition throughout the CRe.

Project Element E.3.

- H10: Decomposition rates will be faster in Western Grand Canyon compared to Lees Ferry due to warmer water temperatures.
- H11: The brown food web (decomposition) will be driven more by microbes in Western Grand Canyon compared to Lees Ferry due a lower abundance of invertebrates and the absence of New Zealand mudsnails.
- H12: Cotton strip assays can serve as an effective monitoring tool to track the brown food web (decomposition and ecosystem respiration).

Project Element E.4.

- H13: Humpback chub and flannelmouth sucker have lower basal metabolic demands than related taxa.
- H14: If humpback chub and flannelmouth sucker have lower basal metabolic demands than related taxa, the ecosystem can sustain large populations of these species despite relatively low primary production and these species can survive through relatively extended periods of low food availability.
- H15: Native fish species in the Western Grand Canyon may be approaching abundances at which food limitation becomes more important in regulating population dynamics.

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 reaches downstream from dams (Bernhardt and others, 2018). In these systems light and disturbance are key factors determining the timing and overall rate of primary production (Bernhardt and others, 2022).

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, with periodic high flow experiments representing the largest disturbances to the ecosystem, albeit generally much smaller floods than experienced under the natural hydrograph (Melis and others, 2012).

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). Findings from the 2018 and 2019 "Bug Flow" experiments show that low and steady flows significantly increase reach-scale rates of primary production (Deemer and others, 2022). In Glen Canyon, GPP may be less sensitive to changes in discharge because variable flow upstream of the Paria is not associated with increased turbidity. Across 143 rivers, the presence of an upstream dam was associated with slower recovery of primary producer biomass following disturbance (Lowman and others, 2024), although this dataset was generally only able to examine trends outside the immediate tailwaters (where oxygen disequilibrium prohibits one station modeling approaches). Preliminary examination of GPP timeseries in the Colorado suggest that recovery of GPP following high flow experiments may depend on the timing of the experiment (Bishop and others, 2024). Downstream, smaller tributary floods may have an equal or greater effect on GPP than do high flow experiments since these floods carry limiting P into the Colorado River and reduce ecosystem pH, making the P more biologically available (Deemer and others, 2023b).

Changes to flow are not the only dam management lever on downstream ecosystem metabolism. Lower Lake Powell elevations are likely having unprecedented impacts on the primary producer communities in the CRe, both through increased entrainment of plankton and through shifts in water quality (Figure 1, H7). Specifically, lower lake elevations are leading to warmer water temperatures (Dibble and others, 2021) and lower but more variable phosphorus concentrations (Deemer and others, 2023b). The lower lake elevations are also affecting the entrainment of biological organisms. While the GCDAMP has largely been focused on entrainment of smallmouth bass (*Micropterus dolomieu*) (Eppehimer and others, 2024), increased entrainment of plankton is also a likely effect of lower reservoir elevations and evidence for this can be observed in the long-term Lake Powell water quality monitoring dataset (Andrews and Deemer, 2022).

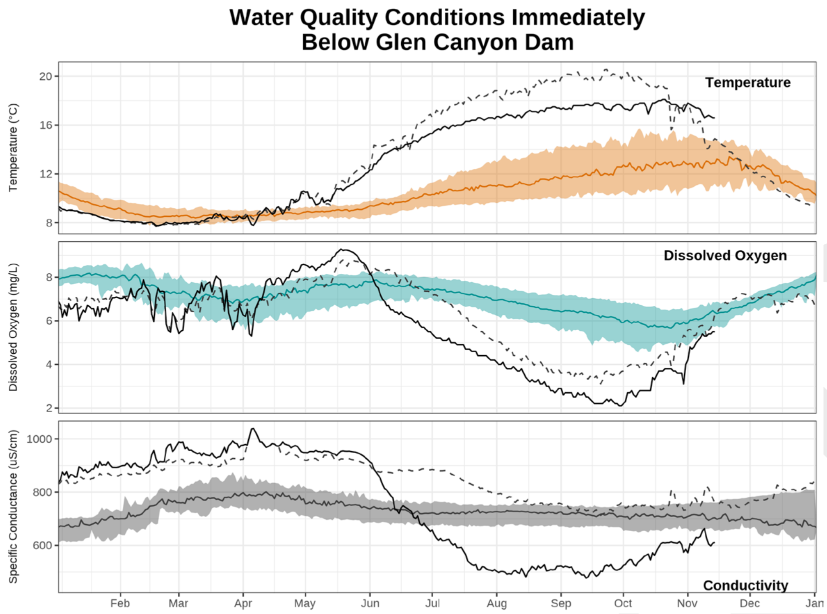

Figure 1. Water quality record from Glen Canyon Dam near Page, AZ (gage #09379901*) for temperature (A) dissolved oxygen (B) and specific conductance (C). Dashed and solid lines show daily median values from 2022 and 2023 respectively (medians are from the continuous data record, logging at 15-minute increments). Colored lines show the long-term median value for each parameter and the orange, blue, and brown color bands represent the daily 10th and 90th quantiles of temperature, dissolved oxygen and specific conductance, respectively. The water quality record represented in this figure contains 12 years of data for temperature and dissolved oxygen, and nine years of data for specific conductance. *Data from this site are currently posted and available through June 2023 at https://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09379901; more recent data are filtered raw values that are awaiting further quality assurance before being posted online. Figure adapted from U.S. Geological Survey (2024).

In 2022, Lake Powell experienced unprecedented warm temperatures, approximately 5℃ warmer than the warmest recorded temperature in the past 50 years (Figure 1). This allows us to test the role of temperature as a driver of metabolic rates. While warmer temperatures are positively correlated with GPP in some Grand Canyon reaches, in other locations GPP appears to be controlled by other factors (Hansen and others, 2023b). In Glen Canyon, warm temperatures in 2022 and 2023 led to elevated GPP and ecosystem respiration (ER), but not to the extent that would be expected based on lab studies (Bishop and others, 2024, Scholl and others, 2024). Experimental work in other systems has demonstrated the capacity for grazers (Kazanjian and others, 2018) and nutrient limitation (Corman and others, 2016) to limit or even reduce primary producer biomass and production under warming temperatures. In other cases, increased nutrient use efficiency with warming water supports substantial increases in stream primary producer biomass and overall production (Hood and others, 2018). In a Glen Canyon decomposition study with three litter sources, two of the litter types showed relatively minor responses to the 2022 warming event (+10°C), whereas the litter type with elevated nutrient content was decomposed at a more elevated rate, suggesting the P limitation regulates the response of the brown food web to temperature increases (Scholl and others, 2024).

Together, these results illustrate that direct effects of warming on GPP and decomposition may be modified by a suite of environmental and biological factors, however it remains unclear how temperature, GPP (including nuisance producers), grazers (including nonnative consumers), and ER interact in the Glen Canyon and throughout the CRe.

Figure 2. Images of nuisance stalked benthic diatom species, taken in the Colorado River near Lees Ferry. Photo credit: Sarah Spaulding.

Distinct producer communities vary in their responses to dam operations (Benenati and others, 1998) and changing environmental conditions upstream (autecological preference for increasing temperature; Blinn and others, 1989; and phosphorus; Bothwell and others, 2014), and thus in their contribution to secondary production (Krist and Charles, 2012). In one example, plausible decreases in P and increases in temperature downstream of GCD may result in the development of nuisance diatom blooms. These taxa are already present throughout the Colorado river, in Glen and Grand Canyons (Bishop and Spaulding, personal observations, Figure 2), and the former commonly thrives in regulated rivers under severe P limitation ($P < 5$ µg/L; Bothwell and others, 2014). The “rock snot” that these blooming taxa produce can reshape macroinvertebrate composition (Larson and Carreiro, 2008; Gillis and Chalifour, 2010) and is also a relatively poor food source which can negatively impact consumer biomass (Furey and others, 2014). In another example, shifting Lake Powell elevations may be affecting the movement of lake phytoplankton (another group of primary producers) and zooplankton downstream. Understanding how producer communities may respond to changes in damoperation (through both changes in flow and changes in water quality) has important implications for the food base and for recreational experience (e.g., Beville and others, 2012).

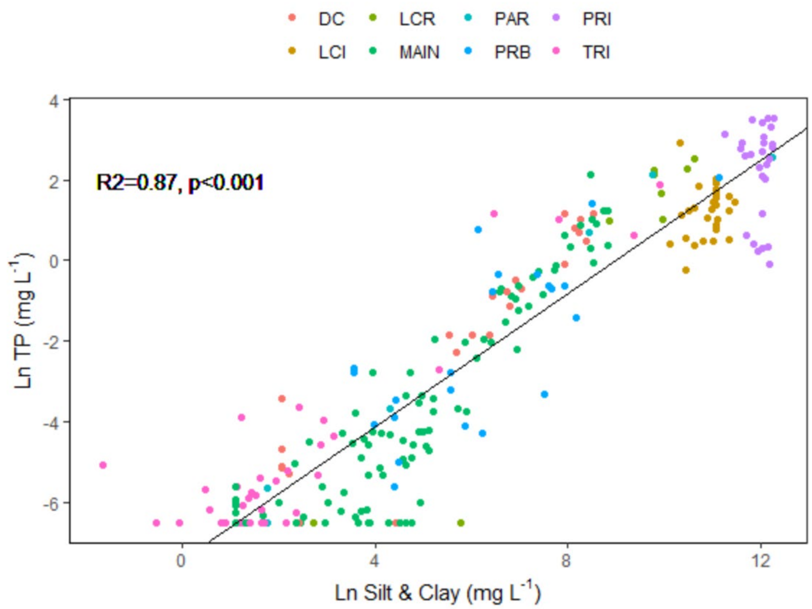

Figure 3. Positive natural log relationship between mainstem and tributary silt & clay concentration and total phosphorus (TP) concentration for samples collected in FY 2021 (n=155). Color indicates sample location and type ("DC"=Colorado River above Diamond Creek, "LCI"=Little Colorado River at Cameron Isco, "LCR"=Little Colorado River grab sample, "MAIN"=mainstem Colorado grab sample, "PAR"= Paria river grab sample, "PRB"=monthly USGS Paria River baseflow grab sample, "PRI"=Paria River Isco sample, and "TRI"= tributary grab sample (generally by community scientist).

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. Declining Lake Powell elevations are generally causing lower P water (that is higher in pH) to be released downstream (Deemer and others, 2023b). Storm-based inputs of P have also been identified as an important source of P to the river (Deemer and others, 2023b). Thus, we expect tributaries to be an increasingly dominant source of P the further you get from GCD, with the dam being the dominant source in the Glen Canyon reach (H1). Given large year to year variation in the summer storm season, we also expect the availability of P to be more variable in Marble and Grand Canyon than in Glen Canyon (H2). While storms flush high concentrations of total P into the CRe (Figure 3), more work is needed to understand the immediate capacity for organisms to take this P up when it enters the ecosystem (and while light availability remains low). We hypothesize that benthic primary producers can capture and store a sizeable fraction of this storm P for later use (H3).

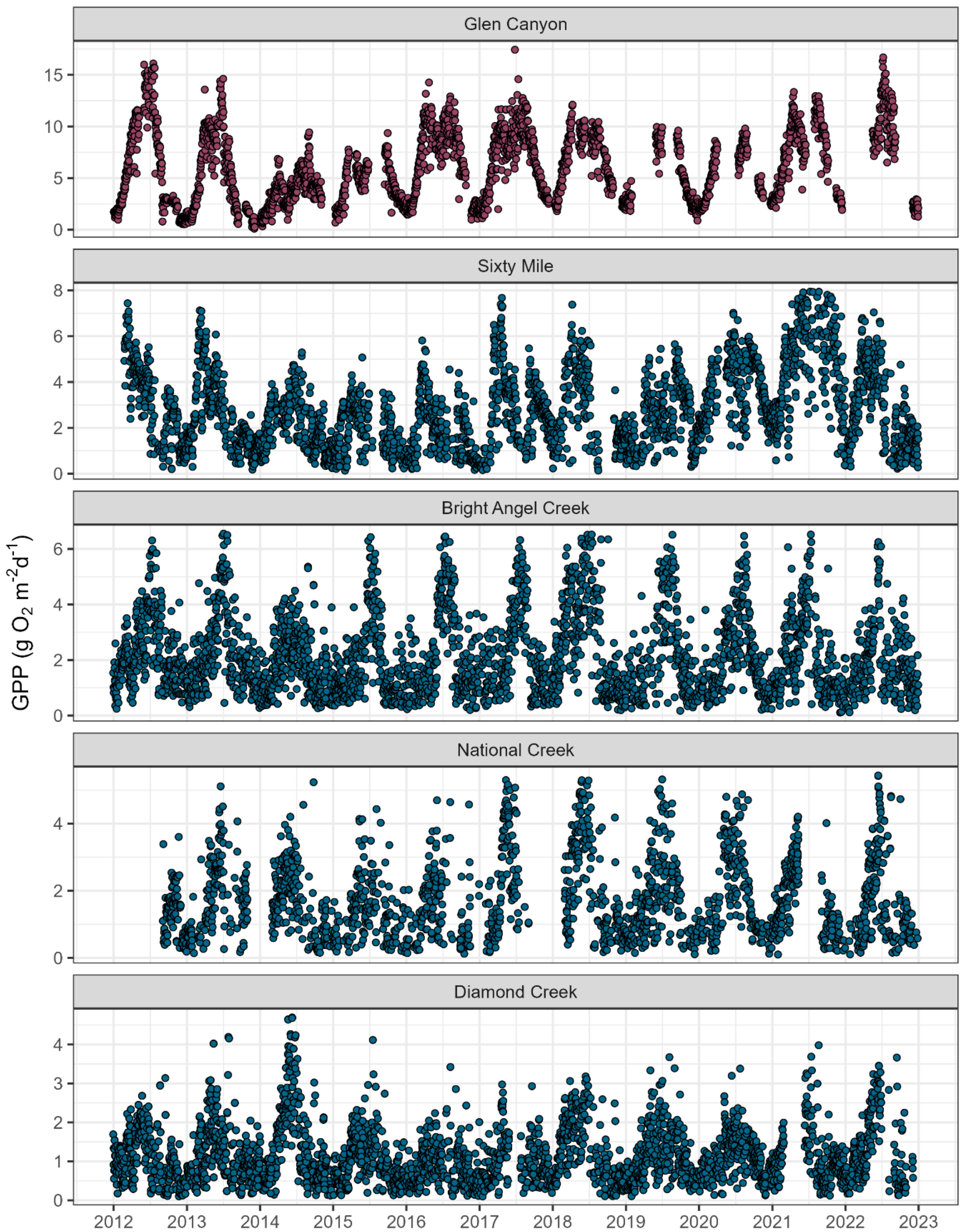

Figure 4. Daily gross primary productivity (GPP) estimates for five dissolved oxygen monitoring reaches of the CRe for the 12 years spanning 2012-2023. Only high-quality estimates are shown for Glen Canyon (R^2>0.9), and only estimates where GPP > 0.1 and Rhat<1.02 are shown for the four downstream sites. From top to bottom, there are 2743, 3148, 3156, 2007, and 3391 daily estimates per site, or 241 days per year on average.

Given the calcium carbonate-dominated geochemistry of the Little Colorado River (LCR; Stone and others, 2018), we expect storms to mobilize much higher concentrations of travertine-bound P than many of the other tributaries.

While most of our measurements of P in the LCR are upstream of travertine formation (at the Little Colorado River at Cameron, AZ, USGS gage 09401200), we expect that during baseflow conditions a substantial fraction of the biologically available P passing Cameron is sorbed to sediments in the reach of the river between Blue Springs and the confluence. This binding of P can happen as gradually increasing pH drives calcium carbonate to precipitate, binding P in the process (Corman and others, 2016; Stone and others, 2018; Deemer and others, 2023a). Sampling in the lower 10 km of the LCR in the summer of 2022 showed that while total river P was high, biologically available P (as soluble reactive P) was consistently near or below detection. This is consistent with previous observations of higher biologically available P near Blue Spring and declining biologically available P moving downstream (Moody and Muehlbauer, unpublished data), suggesting uptake of P by travertine rich sediments. If true, large storms that mobilize LCR sediments are likely to flush this travertine-bound P into the CRe where temperature and pH change may drive biologically available P back into solution, representing a key source of P to the Grand Canyon reach of the Colorado River (H4). This would be consistent with GPP that is more limited by P upstream of the LCR than downstream (H5).

Controls on GPP in the Colorado River and Potential Food Web Implications

Our capacity to estimate daily (and even sub-daily) GPP from continuous dissolved oxygen measurements provides a unique opportunity to identify how dam management (Hall and others, 2015; Deemer and others, 2022) and other ecological drivers affect production at the base of the food web. For example, the very fine timescale of our GPP estimates allow us to link subdaily changes in flow to effects on GPP. During the last work plan, we developed a reproducible workflow for estimating GPP in Marble and Grand Canyon (Hansen and others, *in prep*) including implementation of a light process error model that reduces model bias (Arroita and others, *in prep*). We also demonstrated that higher rates of GPP support higher growth rates of the native flannelmouth sucker (Hansen and others, 2023a), and that these rates can be managed by dam operations (Deemer and others, 2022). Still, we have only scratched the surface of understanding the spatial and temporal patterns in GPP in the CRe and the dam-related levers on these rates. Seasonal patterns are not consistent across river reaches (Figure 4), suggesting unique controls on production by reach. For example, GPP does not scale with temperature in Marble Canyon ("Sixty Mile" site), like it does farther downstream (Figure 5). A better understanding of how the seasonality of reach-scale GPP aligns with key life history stages of native fish could provide insight into times where managing for high GPP will have greatest effect. An understanding of how GPP responds to flow disturbances (e.g., high flow experiments and spike flows), and the timing of flow disturbances, would also be instructive.

Estimating GPP in the Glen Canyon reach is more complicated than further downstream (Payn and others, 2017). Recent improvements in modeling tailwater GPP provide a valuable opportunity to better understand ecological dynamics in the CRe (Bishop and others, 2024).

The Glen Canyon reach exhibits both a spring and a fall peak in GPP (Figure 6). Despite P concentrations being an important driver of secondary productivity in Glen Canyon (Korman and others, 2021; Yard and others, 2023), GPP does not always track P concentrations. This is likely due to a more complex mix of primary producers in this reach (macrophytes, diatoms, cyanobacteria, etc.; H6), each with varying physiological capacities (Lange and others, 2016) and environmental preferences (Spaulding and others, 2021). Some primary producers can access P in riverine sediments, while others are reliant on water column P. GPP derived from different producer communities varies in food web relevance as well, and we expect that the specifics of which drivers are most important to food web-relevant GPP (H5) will be improved by parsing patterns in distinct producer groups. Specifically, we expect that the spring GPP peak in Glen Canyon is driven by benthic diatoms (preferred food source of CRe consumers) growth responding to increased light as well as increased P from GCD outflow (Figure 6; H6). In contrast, we hypothesize that the late summer GPP max is less relevant to consumers, being driven by extensive macrophyte growth responding to increased flow, increased temperature, and stable access to sediment P (H6). Under lower reservoir elevations, a greater fraction of Glen Canyon production may be ascribed to phytoplankton entrained from Lake Powell as well (H7).

The relationship between GPP and fish growth in Marble and Grand Canyon suggests the primary producer community is generally a high-quality food source, but this may change with new water quality regimes under lower Lake Powell elevations. For example, significant proportions of diatom communities throughout the CRe are composed of species (e.g., *Diatoma vulgar*is and *Rhoicosphenia abbreviata*) that have shown sensitivity to experimentally increased temperatures (Blinn and others, 1989), and we hypothesize that recent and predicted high water temperatures downstream would result in decreased biomass for such species (H8). This sensitivity is particularly salient because these species also belong to the diatom guild most preferred by local macroinvertebrate consumers (Colletti and others, 1987; Steinman and others, 1987). Another example of important compositional change relates to potential growth in the abundance and spatial distribution of notable nuisance diatom species, including *Didymosphenia geminata* ("didymo"), and "*Cymbella* sp.", two stalked benthic diatoms that form significant, macroscopic blooms (Bothwell and others, 2014; and see the Central Arizona Project website: https://arcg.is/00fuGz). Both taxa have been observed in the Colorado River downstream of GCD to varying degrees (Ian Bishop and Sarah Spaulding, personal observation, Figure 2). Both taxa in their own ways would likely benefit from decreased P (didymo) and increased temperature (*Cymbella* sp.) and we hypothesize that they may be more widespread than previously believed and that the system is primed for nuisance bloom behavior (H8). Given recent water quality conditions and plausible future scenarios, we propose that CRe diatom composition be revisited to establish a modern baseline of abundance and distribution for the most food web-relevant producer community in the CRe.

The Role of the Brown Food Web in Western Grand Canyon

The role of GPP (i.e., the ‘green food web’) in regulating food web dynamics and fueling fish production near Glen Canyon Dam has been explored in detail (Cross and others, 2011; Yard and others, 2023), however less progress has been made in examining factors governing food webs further downstream, which may act differently from those near the dam. While small patches of algal production associated with tributary junctions can be disproportionally important for fish in downstream turbid environments (Cross and others, 2013; Hansen and others, 2023a), previous work has also demonstrated marked increases in the utilization of allochthonous organic matter by consumers in Western Grand Canyon (e.g., allochthonous detritus alone contributed ~15-35% of fish production and 30-50% of invertebrate production during studies conducted during the period 2006 – 2009 when the amount of native fish biomass was just beginning to increase; Cross and others, 2013). Apart from fueling animal production, increasing reliance on these ‘brown resources’ may also be important for buffering food webs against perturbations (Moore and others, 2004) by incorporating donor controlled slow-energy pathways into to an animal’s consumptive portfolio (Gutgesell and others, 2022; Rooney and others, 2006). Consequently, increasing our understanding of Western Grand Canyon’s brown food web may provide crucial insights for explaining recent increases in native fish populations and predicting how these populations will respond to future environmental changes, such as increasing temperatures and changing nutrients.

While understanding the green food web requires focus on autotrophic processes, such as GPP, elucidating ‘brown food web’ dynamics requires knowledge of heterotrophic processes such as decomposition and respiration. For example, the rate of decomposition can be used to describe whether energy and materials bound in allochthonous organic matter are integrated into aquatic food webs, returned to the atmosphere, or moved into longer-term storage. Materials and energy from very rapidly decomposing organic matter, for instance, may be lost from the system via microbial respiration, whereas more slowly decomposing litter can transfer a greater proportion of carbon to higher trophic levels (Marks, 2019; Siders and others, 2021). Importantly, decomposition rate is strongly governed by both biological and physicochemical factors, such as temperature and nutrients, which will likely result in differences in the fate and processing of organic matter between colder tailwaters and warmer downriver environments (H10). Estimates of respiration, on the other hand, are often used in concert with decomposition to directly link the breakdown of organic matter to heterotrophic biological activity at both substrate-specific and whole-ecosystem scales (Tiegs and others, 2013; Griffiths and Tiegs, 2016; Kominoski and others, 2018). Recent conceptual frameworks have further suggested that ecosystem-scale estimates of respiration may be used to predict the productivity and carrying capacity of higher-level consumers such as fish (Rüegg and others, 2021), thus providing a link between decomposition, respiration, and brown food web dynamics.

As such, exploring connections between decomposition and respiration, and understanding how these processes relate to changes in environmental factors (temperature and nutrients) offers an exciting opportunity to disentangle the brown food web in Western Grand Canyon.

The use of cotton-strip assays to measure microbially mediated organic matter decomposition has recently emerged as an effective and standardized tool to estimate decomposition across unprecedented spatial scales (Tiegs and others, 2019) and multi-annual time periods (Mancuso and others, 2022), and has been implemented into monitoring strategies (Young and Collier, 2009; Carballeira and others, 2020). Although cotton does not capture the full complexity of natural litter decomposition (including the impact of macroinvertebrates) the benefits of using this technique include 1) being able to directly compare to global datasets (Tiegs and others, 2019), 2) consistent and easily reproducible methodology, and 3) similar sensitivity as natural litter to environmental drivers including temperature and nutrient concentrations (Griffiths and Tiegs, 2016; Costello and others, 2022). Given that the Western Grand Canyon largely lacks macroinvertebrates that are commonly associated with the breakdown of organic matter (e.g., *Gammarus*, mudsnails; Cross and others, 2013), we expect that decomposition will be primarily driven by microbes (H11), and thus cotton-strip assays will provide a powerful tool to track spatial and temporal changes in the Western Grand Canyon brown food web (H12).

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 downstream 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. Project 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 fishes, 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 (H13). 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 (H13) they will require substantially less food to maintain a given weight, and it may be possible to sustain much larger biomasses (abundances) of native fishes at a given food availability (H14). 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 fishes 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 fishes, we have observed similar changes in fish condition and perhaps reproduction; however, impacts on growth and survival are either smaller or masked by effects of environmental factors. As a result, adult abundances of native fishes appear to be more stable in response to declines in food availability, but reproduction is quite variable. Nonetheless as native fish population approach their carrying capacity, we hypothesize that long-term changes in environmental conditions (e.g., from changing quality of water released from Lake Powell) will play an important role in regulating overall abundances (H15). Additions of higher trophic levels (i.e., piscivorous, warm-water nonnatives like smallmouth bass), are also expected to impact production and consumption at lower trophic levels and ecosystem models could provide another mechanism for predicting the potential impacts of nonnative expansions on native fish population sizes.

Proposed Work

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

Bridget Deemer[1], Ian Bishop[1], Robert Hall[2], David Topping[1], Tom Sabol[1], Theodore Kennedy[1], Charles B. Yackulic[1], Sasha Reed[3]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Flathead Lake Biological Station, University of Montana
[3]U.S. Geological Survey, Southwest Biological Science Center

This project element aims to characterize the major sources and storage sites for P in the Colorado River as well as to understand controls on P export from the system.

We propose to leverage samples collected and analyzed during the last work plan to develop site-specific relationships between P and suspended sediment concentrations. These relationships will then be used to construct a mass balance P model, which we expect we can extend across tens of years where suspended sediment concentrations have been measured but P has not. On shorter time scales relevant to primary production, tributary storms can be a significant source of biologically available P to the Colorado River (Deemer and others, 2023b) and may serve as a direct source of P to benthic producers, given that algal taxa living in low-P environments can rapidly increase P uptake rates and store excess P when it becomes available ("overplus P uptake"; Rier and others, 2016). P captured by this process may offset some of the negative impact of increased turbidity on productivity by boosting growth after such events have passed. This process would also redirect additional P from downstream export into local food webs. We propose to examine this process downstream of major tributaries and determine both the scale of excess P uptake and how it varies among distinct algal producers (e.g., diatom and cyanobacterial benthic communities). Ultimately, this element will inform GPP modeling efforts described in E.2, allowing us to link P to rates of primary production (especially in further downstream sections where tributary inputs potentially override the influence of variation in the P in dam releases).

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) Quantify overplus P uptake during times of elevated P loading (during storms).
3) Construct a model that relates tributary silt and clay inputs to phosphorus so that phosphorus concentrations in the Colorado River can be hindcasted.

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 export (or P that is transported downstream of the Colorado River above Diamond Creek near Peach Springs, AZ gage). This will be done using empirical relationships between P and silt-and-clay, based on data collected during the last work plan (Figure 2) and will also utilize estimates of P equilibrium from sorption/desorption experiments that are being conducted this summer (FY 2024). Ideally, such empirical relationships could be extended to link P concentrations with turbidity, which is an easily measured water quality parameter that is collected as part of Project A. Such a modeling approach could be combined with unfunded turbidity modeling work proposed in Project B4 to develop predictive models of P.

We will compare P loading from GCD with P loading from tributary storms to characterize the predominant source of P in different river reaches (H1). Monthly measurements at the outflow to Glen Canyon Dam are currently taken as part of the Interagency Lake Powell Water Quality Monitoring Program (see 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.

We also hypothesize that benthic algae downstream of Lees Ferry sustain elevated GPP during the monsoon season in part through a nutrient acquisition strategy known as “overplus P uptake” (Harold, 1966; e.g., Lapointe and others, 2024), in which algal cells adapted to low-P environments opportunistically uptake extra P during storm events and store it for later use when baseline low-P conditions resume (H3). To assess this capacity and the extent to which it represents a significant retention of available P during such storm events, we plan to measure P loading and P uptake at the Paria River confluence 1 day before, during and up to 7 days after a summer storm event in FY 2025. Multiple algal substrates (e.g., cyanobacteria- and diatom-predominant biofilms) will be sampled to assess variable uptake rates of polyphosphate, the most common form in which cellular P is stored. Total P of the benthic samples will also be measured, as the extracellular biofilm matrix these algae construct is itself known to absorb significant quantities of P (Sundareshwar and others, 2011). Algal substrate sampling will be paired with frequent sampling of P in the Paria River outflow during the storm event, which allows us to relate uptake rates of the various algal communities back to P loading intensity of this specific storm event. Finally, in addition to measuring uptake rates, a benthic fluorometric instrument (BenthoTorch, bbe-Moldaenke) will be used to measure changing producer biomass during the post-event period, which in combination with nearby DO-based reach-scale GPP measurements will allow us to assess how excess P is utilized in the short term after the storm event concludes.

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

Ian Bishop[1], Lindsay Hansen[1], Kimberly Dibble[1], Bridget Deemer[1], Dan Buscombe[2], Mike Yard[3], Bob Tusso[1], Robert Hall[4], Theodore Kennedy[1], Charles B. Yackulic[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2] U.S. Geological Survey, Western Ecological Research Center, Santa Cruz, CA
[3] U.S. Geological Survey, *retired*
[4]Flathead Lake Biological Station, University of Montana

This project element provides the underlying modeling to support the natural processes GPP metric and aims to disentangle the drivers of both rates and types of riverine primary production and their link back to fish production. We aim to disentangle some of these drivers of ecosystem production by combining the highly resolved long-term information about riverine turbidity, silt and clay concentrations, solar inputs, discharge, and GPP (via continuous oxygen and temperature measurements – data that are collected as parts of the Lake Powell project, Project A.2, and Project E), with improved additional information about P (Project Element E.1). While we have until now primarily focused on identifying environmental controls on reach-scale metabolism, here we propose to examine the relative role of distinct algal communities (multiple diatom ecological guilds, cyanobacterial mats, macrophytes, macroalgae) in shaping whole river production. To achieve this, we propose multiple projects that more finely resolve primary producer dynamics beyond bulk, reach-scale averages. These include 1) estimation of group-specific metabolic rates via in-situ chamber experiments, which leverage investments made in the current work plan to study fish energetics; 2) continuation of machine learning-based vegetation mapping in Glen Canyon; 3) surveying benthic diatom diversity downstream of Lees Ferry, which would help establish a baseline for multiple nuisance diatom taxa ahead of possible temperature and P change in the reach; and 4) leverage a long-term phytoplankton composition dataset (Deemer and others, 2023a) to assess the role that reservoir phytoplankton have on downstream production dynamics. We expect the continued work to elucidate controls on GPP together with producer-specific investigations will help reveal critical controls on CRe productivity and allow for informed management decisions to support relevant LTEMP resource goals.

Objectives

1) Determine which environmental drivers are most important in shaping GPP and the extent to which driver importance varies throughout the CRe.
2) Investigate producer community-specific relationships to river-wide patterns and drivers of GPP.
3) Survey CRe benthic diatom community during peak productivity periods and establish a modern baseline, including species checklists and distribution maps, for key/nuisance taxa.
4) Develop a semi-automated aquatic vegetation classification system to facilitate detection of change in primary producer community structure.

Methods

We will continue developing estimates of GPP at the daily timestep to add to the continuous record that has been developed at the USGS gages: Colorado River above Little Colorado River near Desert View, AZ, “Sixty Mile” 09383100, Colorado River near Grand Canyon, AZ “Bright Angel” 09402500, Colorado River above National Canyon near Supai, AZ “National” 09404120, and Colorado River above Diamond Creek near Peach Springs, AZ “Diamond” 09404200 and within Glen Canyon via dissolved oxygen measurements at two sites not served online (Figure 4). Bayesian methods have been developed for Marble and Grand Canyon using a light process error model (Arroita and others, *in prep*) and a reproducible workflow has been developed to update models based on continuous water quality data collected as part of Project A.

For Glen Canyon, modeling is complicated by the combination of sub-daily variation in flow and oxygen disequilibrium (due to the bottom water and mid-water releases from Lake Powell). We are currently developing a two-station method that builds upon earlier more time intensive modeling approaches (e.g., Payn and others, 2017) and that can estimate GPP fast enough to develop much longer time series (Bishop and others, 2024; Figure 4 top panel).

We are excited to explore controls on GPP time series throughout the CRe and propose to examine 1) response to disturbance, 2) evidence of nutrient limitation and lagged response to storm-based phosphorus inputs, and 3) reasons for asynchronous seasonal patterns throughout the river. We will implement a new approach to modeling primary producer biomass from GPP time series (Blaszczak and others, 2023) to quantify the resilience of the ecosystem to disturbance, and to examine the controls on this resilience. We will also use autoregressive integrated moving average (ARIMA) models for post-estimation analysis of controls on GPP.

The purpose of the proposed spring and fall benthic diatom surveys is to comprehensively document the distribution and character of the algal group most directly connected to local and valued aquatic food webs. It has been nearly 50 years since Czarnecki and others (1976) collected and analyzed benthic diatom communities from Lees Ferry down through the Western Grand Canyon, and much has changed since then. Dominant invertebrate grazer communities have shifted with the maturing presence of multiple introduced species (*Gammarus* and New Zealand mud snails; (Cross and others, 2010), hydrology has evolved through increasingly constrained load-following and regular high flow experiments (see Figure 2 in Sankey and others, 2018), and more recently elevational change in Lake Powell has driven strong changes to water quality, most notably temperature and phosphorus concentration (Dibble and others, 2021; Deemer and others, 2023b; U.S. Geological Survey, 2024). This project will help clarify how resilient the diatom base of the food web is to recent environmental change. It will also establish a modern (molecular) baseline for the abundance and distribution of this important producer group throughout the canyons, including for salient, ecologically relevant taxa such as nitrogen-fixing (e.g., *Epithemia* spp.) and nuisance bloom-producing diatoms (Figure 2).

For the FY 2025-27 work plan, these surveys will be opportunistically conducted by accompanying 2 seasonal monitoring river trips (April-May and September FY 2025), periods during which annual GPP peaks. At approximately 20 mainstem and confluence sites, a representative set of benthic substrates will be sampled, combined, and processed for microscopic and genetic metabarcoding analysis. Ian Bishop, a recently hired post-doc at GCMRC, has extensive expertise in collecting and analyzing such communities using both traditional microscopic and modern genomic methods, which will facilitate comparison to past and future literatures. Additional samples will be collected for targeted, low-effort microscopic scanning to improve spatial distribution resolution for important taxa (e.g., didymo). The primary goal here is to produce species-level checklists, abundances, and distributional patterns, which will be related back to key environmental drivers.

To further contextualize these data, we will assess the extent to which they correspond to two active independent data streams: 1) the monthly sampling of phytoplankton composition for lower Lake Powell and Lees Ferry (20+ years of data), and 2) longitudinal patterns of GPP measured via continuous DO monitoring throughout the study area.

The purpose of the vegetation mapping project is to finish the development of a machine learning model that can be used to classify images and produce maps of submerged aquatic vegetation in Lees Ferry. The information gained from this project will serve as a baseline to answer questions related to the effects of dam operations and reservoir conditions on dominant primary producers that fuel the "green" food web consumed by aquatic invertebrates and fish. In particular, this project aims to measure long-term responses in primary producers to changing water temperature or nutrient availability from Lake Powell, and short-term responses to LTEMP Flow Experiments that disturb the littoral edge through prolonged desiccation followed by subsequent scour. Such scour, as was seen in underwater imagery associated with the Spring Disturbance Flow (2021) led to aquatic vegetation removal and transport of organic matter that likely fueled the "brown" food web downstream.

In previous work plans we made progress on the development of a deep convolutional neural network model by 1) utilizing image processing software to manually label vegetation classes on underwater images, 2) creating a library of vegetation labels to train model development, 3) compiling images to feed into the model framework, and 4) running segmentation models on >50,000 images. We propose to focus work in the FY 2025-27 work plan on analyzing existing imagery, refining and publishing the deep learning model, and creating maps from which to compare future disturbance events or community change over time. This work will include an analysis of flow impacts to aquatic vegetation composition and cover in two sites that overlap long-term rainbow trout monitoring sites in Lees Ferry.

Project Element E.3. Understanding the Energetic Basis of the Food Web in Western Grand Canyon

Eric Scholl[1], Ian Bishop[1], Bridget Deemer[1], Theodore Kennedy[1], Charles B. Yackulic[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

This project element aims to understand controls on the base of the food web in Western Grand Canyon. In the Western Grand Canyon, humpback chub populations have increased dramatically in the last decade, but the underlying causes for this change are unknown. One hypothesis is that warming water temperatures are supporting a more productive aquatic insect food base. All else being equal, warming water temperatures are expected to increase rates of heterotrophic metabolism and decomposition (brown food web) faster than rates of primary production (O'Connor and others, 2009; Demars and others, 2011), suggesting that the brown food web is serving as an important conduit for fish food in this part of the river.

Alternatively, a recent revisitation of decomposition rates in Glen Canyon suggests that low P concentrations suppressed decomposition rates during 2022 warm-water releases, leading to no detectable difference in the decomposition rate of two litter types despite ~10 °C warmer temperatures (Scholl and others, 2024). This project aims to quantify rates and drivers of decomposition, substrate-scale respiration, and whole-ecosystem primary production and ecosystem respiration in the Western Grand Canyon by deploying a miniDOT (PME) logger for metabolism estimates and, to the extent that outside funding continues, leveraging a new gage site near Columbine.

While turbulent whitewater conditions preclude estimation of respiration rates in most of Grand Canyon, we expect the lower gradient reach approaching Pearce Ferry to support paired estimates of GPP and ecosystem respiration We also propose targeted decomposition experiments on natural litter and cotton strip assays to understand controls on detritivore vs. microbe-driven decomposition and how changes in temperature, nutrient availability, and litter quality may influence food availability for higher trophic levels. By pairing integrative estimates of ecosystem metabolism with finer-scale decomposition and respiration measurements, our approach will offer a uniquely holistic perspective on the energetic pathways underpinning food webs in Western Grand Canyon.

Objectives

1) Estimate GPP and ER for Western Grand Canyon and contrast with Glen Canyon trends and drivers.
2) Compare decomposition rates between Lees Ferry and Western Grand Canyon using a native leaf source and standardized cotton strips.
3) Explore the relative influence of macro-detritivores (e.g., invertebrates) vs. microbes on governing decomposition in Lees Ferry and Western Grand Canyon.
4) Link substrate-specific respiration estimates on cotton strips to whole-ecosystem respiration measurements.
5) Evaluate the potential for using standardized cotton strips as a large-scale and long-term monitoring tool to assess organic matter dynamics in Western Grand Canyon.

Methods

Leaf decomposition at both Lees Ferry and Western Grand Canyon will be estimated during one season following protocols outlined by Scholl and others, 2024. We will collect leaves from the banks of the Colorado River in the fall of 2024 and allow the litter to dry in the laboratory prior to the start of the experiment. In the laboratory we will measure 4 g dry mass of leaflitter into 50 (5 replicates*5 collections [day 1,2,7,21,84]*2 locations) coarse mesh and 50 fine mesh packs. Different mesh sizes will be used to isolate the potential effects of larger macroinvertebrate consumers on decomposition. Leaf packs will be deployed at locations with similar environmental conditions (e.g., low velocity) at both sites.

At each site we will submerge five separate chains and randomly tie five coarse mesh and five fine mesh packs to each chain. On each collection date we will randomly collect one coarse and one fine mesh bag per chain, place the packs into labeled bags, and store on ice until laboratory processing. In the laboratory, samples will be rinsed, sorted from invertebrates, dried, weighed, and combusted to estimate ash-free dry mass (AFDM) of leaf packs throughout the experiment. Percent leaf mass remaining (AFDM) will be natural log-transformed and regressed over time and degree days to estimate decay rate (k) and temperature corrected decay rate (k_{dd}). We will then compare decay rate slope estimates among mesh sizes and locations to examine the effects of location, temperature, and invertebrates vs. microbes on decomposition.

At each site where natural litter bags are placed, we will also deploy standardized cotton strips following protocols outlined in Tiegs and others, 2013. We will construct 50 cotton strips (each ~80 mm x 25 mm strip from heavy-weight cotton fabric) so that 5 replicates will be collected on the same dates at natural sources (see above). Upon removal from the water column, we will measure biofilm respiration in stream-rinsed jars pre-fixed with non-invasive dissolved oxygen optodes (PreSens Precision Sensing GmbH, Regensburg, Germany; Deemer and others, 2023a). Initial dissolved oxygen (DO) measurements will be recorded for each jar, which will then be stored in stable temperature in the dark for 2-4 hours, after which final DO measurements will be taken. Three controls on each date will be used to measure ambient respiration in the water column and respiration rate for each strip will be estimated as

$$((DO_{stream} - DO_{strip\ post}) - (DO_{stream} - DO_{control\ post}))\ X\ VH_2O\ jar\ /\ m_{strip}/t$$

where DO_{stream} is the initial DO concentration of river water, $DO_{strip\ post}$ is the DO concentration after incubation, $DO_{control\ post}$ is the DO concentration of the control jars after incubation, VH_2O jar is the volume of river water used, m_{strip} is the dry mass of the cotton strip, and t is the incubation duration.

Following respiration measurements, each strip will be placed in a tray, gently cleaned using a paint brush and 95-100% ethanol and stored in individual aluminum envelopes. In the laboratory, each strip will be dried at 40°C, weighed, and measured for tensile strength using a Mark-10 tensiometer affixed to a motorized stand. The rate of tensile strength loss will be estimate as

$$k_{strip} = (-\ln(T_c/T_{sc}))/days$$

where T_s is the maximum tensile strength recorded for each incubated strip, T_{sc} is the mean tensile strength of the control strips, and days is incubation duration in days. Similar to natural leaves, we will also isolate the effects of temperature by standardizing for degree days.

At each site we will measure daily water temperature using either the USGS Colorado River at Lees Ferry gage (09380000) or a submerged HOBO® temperature logger in Western Grand Canyon. Three replicates of total and dissolved P will be measured at three time points throughout the decomposition experiment (n =18; 3 replicates*3 times * 2 locations) following protocols outlined by Deemer and others (2023b).

Finally, estimates of whole-ecosystem metabolism (GPP and ER) will be made using a miniDOT and protocols outlined in Deemer and others, 2022. We expect to successfully estimate ER in Western Grand Canyon given the relatively minimal whitewater in this reach (whereas microbubble entrainment precludes ER estimation at the long-term gage sites in Figure 5; Hall and others, 2015).

Project Element E.4. Linking Ecosystem Metabolism to Higher Trophic Levels

Charles B. Yackulic[1], Kimberly Dibble[1], Drew Eppehimer[1], David Ward[2], Eric Scholl[1], Eric Frye[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2] U.S. Fish and Wildlife Service

The goal of this project is to develop ecosystem models that incorporate data collected at multiple trophic levels. This modeling will leverage ecosystem production rates estimated in Project Elements E.2 and E.3. together with estimates of consumption by fish populations to understand how bottom-up and top-down processes interact to drive ecosystem dynamics and determine carrying capacity for consumers (Figure 7). This type of approach was recently taken to understand energetic constraints on the rainbow trout population in Glen Canyon (Yard and others, 2023). The modeling will combine estimates of species and size class specific somatic growth and survival rates with estimates of basal metabolism to estimate energetic demand for individual fish, which will then be scaled up with species and size class specific abundance estimates to estimate the consumption required to support observed abundances, survival, and growth rates. These estimates of consumption will then be compared with estimates of energy production at lower trophic levels (i.e., ecosystem metabolism) or invertebrate availability (i.e., drift measurements) accounting for the transfer efficiency of energy across trophic levels to understand how changes in energy production impact fish population dynamics.

We will combine fish population abundances and somatic growth estimates from fixed sites (i.e., TRGD 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 (Project 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 and nonnative fish 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 a fish (Norin and Malte, 2011; Chabot and others, 2016b).

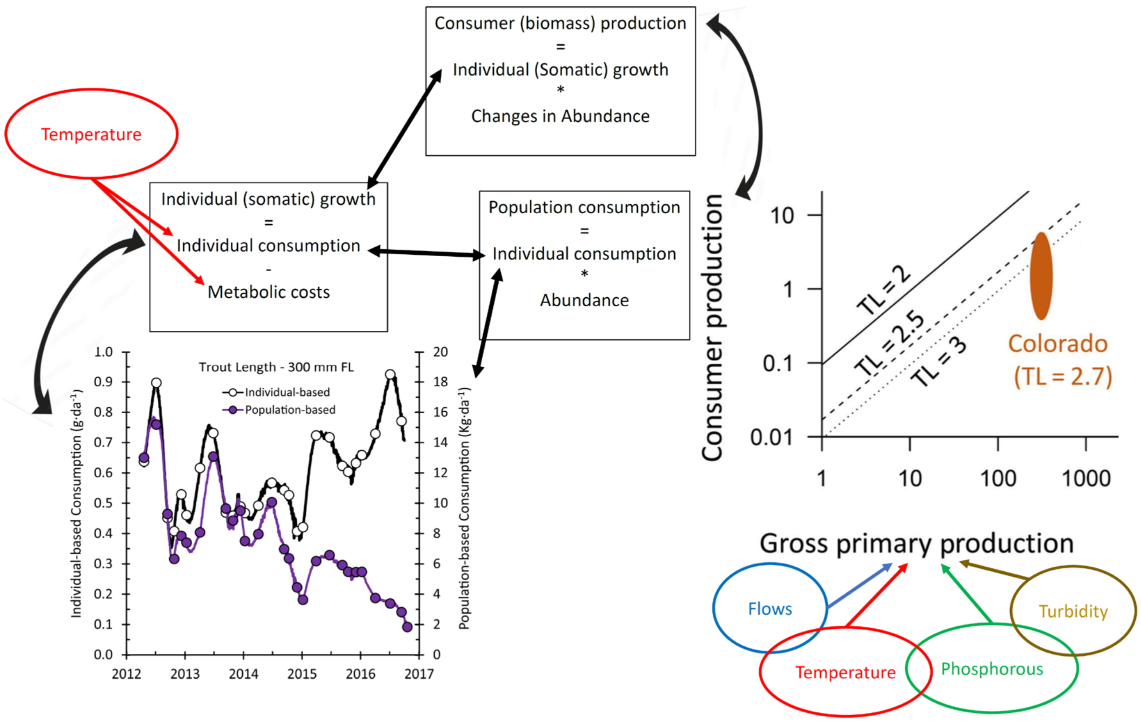

Figure 7. Conceptual model linking primary production to fish consumption, production and ultimately individual growth and population dynamics. Many of the processes linking primary production to fish population dynamics are affected by environmental drivers (e.g., flow, turbidity, thermal, and nutrient regimes), and we only identify a few linkages here. TL refers to trophic level and the value of 2.7 is based on prior studies of flannelmouth sucker (*Catostomus latipinnis*) (Cross and others, 2013). Figure is based on modification of figures presented in Rüegg and others (2021) and Yard and others (2023).

Laboratory experiments will be used to determine the standard and active metabolic rates of large-bodied native and nonnative fishes in the Grand Canyon 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 data on primary production, insect drift, fish growth, and population size 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 species such as 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 straightforward. 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 or elsewhere. Fish will be kept in recirculating tanks at ambient temperature and fed a maintenance diet until trials commence. Standard metabolic rates of individual fish will be measured using automated intermittent flow respirometry in a Loligo Systems Core Resting Respirometer. 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 recirculating pump. Individual fish will be placed in each chamber to acclimate, and a series of oxygen consumption measurements will be taken. Active metabolic rates will be measured in a similar manner, but specimens will be actively chased in a tank prior to placement in each chamber (Killen and others, 2021). Multiple size classes of fishes will be used in this experiment to allometrically scale metabolic rates. Individual 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 integrated difference equations that estimate quantities like transfer efficiencies using priors 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.

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 quantify the capacity for Colorado River algae and macrophytes to take up and store excess P when storm events increase P concentrations.

Products

- Two journal articles describing P budget in Glen and Grand canyons, one focusing on the role of the LCR and one describing a whole system budget.
- One journal article describing excess P uptake by river producers and links between pulse storm P inputs and overall riverine primary production.
- A model that hindcasts 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 how distinct algal and macrophyte communities each shape trends 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. Lastly, we expect to establish a modern baseline for the most food web-relevant producer community in the CRe (diatoms) by surveying their abundance and distribution for the first time in nearly 50 years.

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.
- One journal article describing a deep convolutional neural network model for aquatic vegetation image segmentation and classification.

- One journal article describing pulse flow effects on aquatic vegetation communities in Glen Canyon.
- One journal article summarizing the current diatom communities inhabiting the CRe, including for nuisance taxa such as *Didymosphenia geminata*.

Project Element E.3.

Outcomes

- We expect that this this project element will help us gain an understanding of the dynamics and potential drivers (e.g., temperature and nutrients) of whole-ecosystem stream metabolism and the brown food web underpinning native fish populations in Western Grand Canyon. We also expect that this project will provide important information to guide and refine ecosystem models that are discussed in Project Element E.4.

Products

- One journal article that compares the drivers of decomposition and respiration rates between Lees Ferry and Western Grand Canyon, enhances our understanding of invertebrates vs. microbially-driven organic matter processing in Western Grand Canyon, and explores the utility of using a standardized methodology (i.e., cotton strip assays) to track spatial and temporal variability in decomposition in Grand Canyon.

Project Element E.4.

Outcomes

- We expect that this project element will provide a better understanding of the amount of energy needed for native and nonnative 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. This information could be used to develop an estimate of the carrying capacity of Western Grand Canyon to support fish communities.

Products

- One journal article that reports on the standard and active metabolic rates of native and nonnative fishes that lack parameter estimates (i.e., inputs into the bioenergetics and/or ecosystem model for species such as humpback chub and flannelmouth sucker).

- 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 mathematical ecosystem model linking flow, temperature, nutrients, and energy needs to multiple trophic levels.

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Budget

Fiscal Year 2025									
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
E.1. Phosphorus budgeting in the Colorado River	$64,625	$0	$13,539	$1,225	$0	$0	$17,307	**$96,696**	
E.2. Rates and composition of primary producers in the Colorado River	$149,106	$4,000	$63,045	$3,150	$0	$0	$47,808	**$267,109**	
E.3. Understanding the energetic basis of the food web in Western Grand Canyon	$61,053	$1,000	$3,408	$0	$0	$0	$14,271	**$79,732**	
E.4. Productivity at higher trophic levels	$67,249	$0	$3,000	$0	$0	$0	$15,314	**$85,563**	
Total Project E	**$342,034**	**$5,000**	**$82,992**	**$4,375**	**$0**	**$0**	**$94,699**	**$529,101**	**$45,307**

Fiscal Year 2026									
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
E.1. Phosphorus budgeting in the Colorado River	$53,103	$2,000	$3,500	$700	$0	$0	$13,403	**$72,706**	
E.2. Rates and composition of primary producers in the Colorado River	$137,167	$5,250	$47,092	$1,750	$0	$0	$43,225	**$234,483**	
E.3. Understanding the energetic basis of the food web in Western Grand Canyon	$30,258	$0	$0	$1,750	$0	$0	$7,234	**$39,242**	
E.4. Productivity at higher trophic levels	$72,198	$0	$3,000	$0	$0	$0	$16,995	**$92,193**	
Total Project E	**$292,727**	**$7,250**	**$53,592**	**$4,200**	**$0**	**$0**	**$80,856**	**$438,624**	**$37,912**

Fiscal Year 2027									
Project E Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
E.1. Phosphorus budgeting in the Colorado River	$103,785	$2,000	$3,500	$0	$0	$0	$25,573	**$134,857**	
E.2. Rates and composition of primary producers in the Colorado River	$89,894	$6,500	$18,044	$1,750	$0	$0	$27,188	**$143,376**	
E.3. Understanding the energetic basis of the food web in Western Grand Canyon (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
E.4. Productivity at higher trophic levels	$53,426	$0	$3,000	$0	$0	$0	$13,204	**$69,629**	
Total Project E	**$247,104**	**$8,500**	**$24,544**	**$1,750**	**$0**	**$0**	**$65,964**	**$347,863**	**$30,343**

Project F: Aquatic Invertebrate Ecology

Investigators

Theodore A. Kennedy[1], Kathrine Behn[1], Anya Metcalfe[1], Morgan Ford[1], Eric Scholl[1], Cheyenne Szydlo[1], David Lytle[2]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Department of Integrative Biology, Oregon State University

Project Summary and Purpose

The primary focus of Project F is continuation of long-term monitoring needed to track ecosystem response to Macroinvertebrate Production Flows (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 (Kennedy and others, 2016; Miller and others, 2020; Figure 1). In May–August of 2018–2020 and 2022, Glen Canyon Dam operations were experimentally modified to evaluate whether low steady flows on weekends would 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 community science monitoring of aquatic insects and bat activity (F.1; note that bat monitoring is currently unfunded), monitoring of invertebrate drift (F.1 and F.2), monitoring of invertebrate communities in tributaries and the mainstem Colorado River using environmental-DNA (eDNA; F.3), and quantifying feeding habits, parasite loads, and overall health of native and nonnative fishes using DNA analysis of feces and stable isotope analysis of fin clips (F.4).

Research and monitoring of invertebrates and fish feeding habits 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. Data on invertebrate populations and fish feeding habits also aid interpretation of seasonal and annual trends in humpback chub (*Gila cypha*; Project G), rainbow trout (*Oncorhynchus mykiss*; Project H), and smallmouth bass (*Micropterus dolomieu*; Project I), because aquatic invertebrates represent the food base for these species of fish during some, or all, of their life-stages. 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.

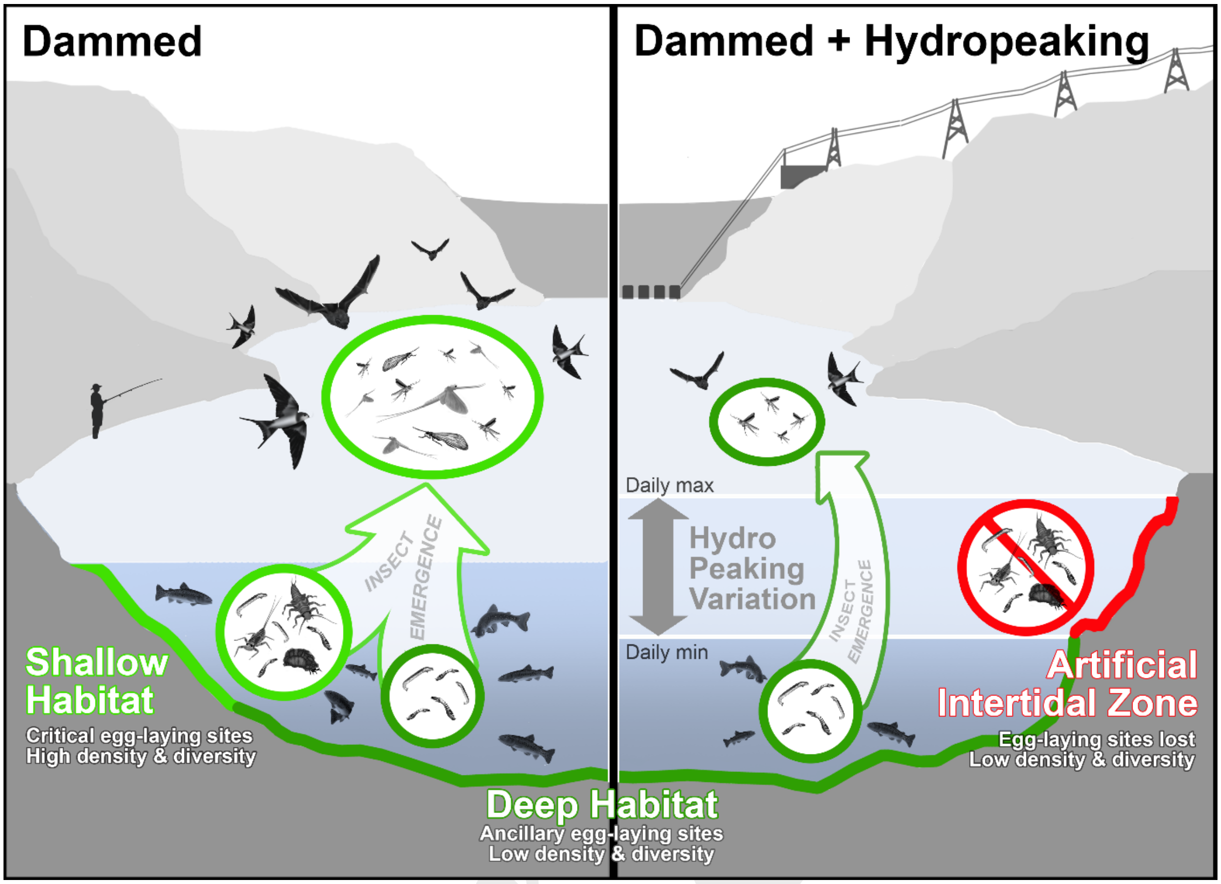

Figure 1. Conceptual model highlighting the essential role that aquatic insects play in river food webs. Ecologically important insect groups such as mayflies, stoneflies, and caddisflies cement their eggs along river-edge habitats, making them especially sensitive to hydropower production practices 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. From Kennedy and others, 2016.

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 FY 2025-27. Testing of experimental Bug Flows in 2018-2020 and 2022 has provided a wealth of data and strong support for the below hypotheses, which were first included in the FY 2021-23 TWP:

- H1: Bug Flows increase the abundance of midges in the CRe by improving survival of sensitive insect eggs (Figures 1, 2).
- H2: Bug Flows increase the abundance of EPT (Ephemeroptera [mayflies], Plecoptera [stoneflies], Trichoptera [caddisflies]) in the CRe by improving survival of sensitive insect eggs (Figures 1, 2).

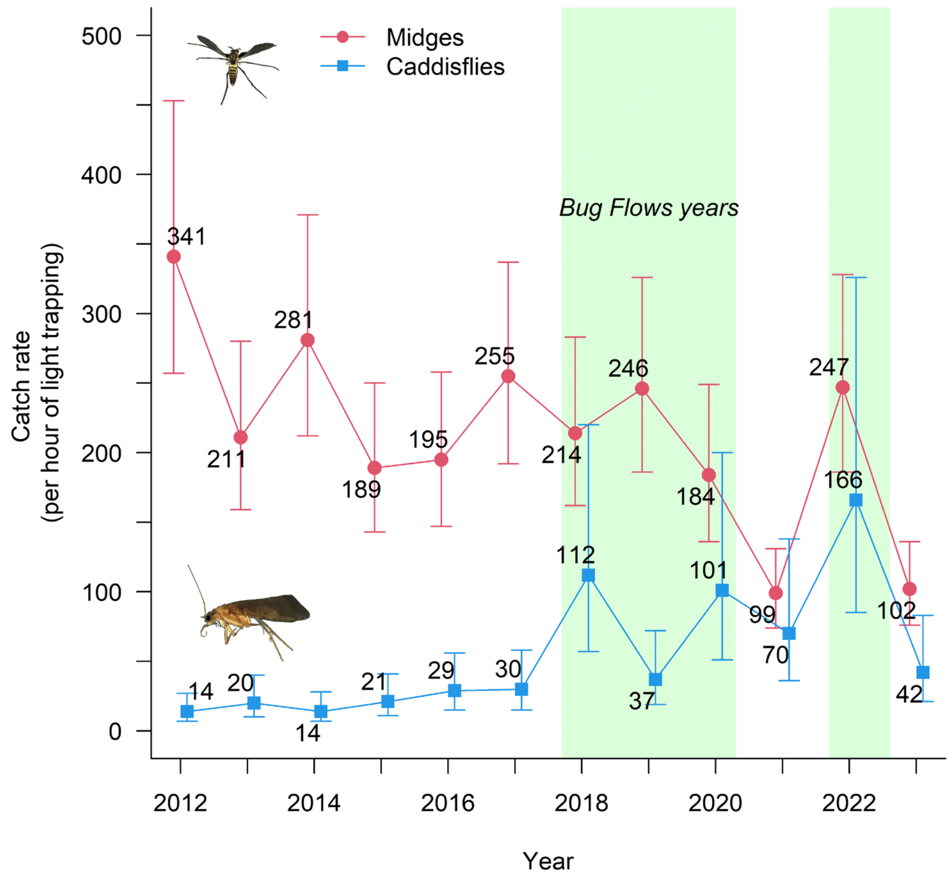

Figure 2. Community science light trap catches of midges and caddisflies by year (solid lines and circles). Years of Bug Flow testing are highlighted in green. Annual average values appear above each point and are estimated from a mixed-effects model that accounts for variation in sampling effort across reaches and across years. Error bars represent one standard error. There is strong model support for a positive Bug Flow effect on catch rates of both caddisflies and midges i.e., inclusion of Bug Flows as a fixed effect lowers the AIC by 28 and 36 for midge and caddisfly models, respectively; note that AIC decreases >8 are considered strong model support for a given predictor. Inclusion of High Flow Experiments, which have occurred sporadically over the period of record, does not improve model performance based on AIC. We are unable to evaluate whether environmental drivers such as temperature or suspended sediment conditions improve model performance over the period of record owing to staffing vacancies in Project A, which were only recently filled.

Bug Flows are associated with significant increases in the abundance of key invertebrate prey items (Figure 2) that in turn fuel growth of fishes, bats, and other wildlife throughout the Colorado River ecosystem (Cross and others, 2013; Metcalfe and others, 2023). Bug Flows also leads to ecologically meaningful increases in gross primary production (GPP) throughout the CRe (i.e., 40% increase) resulting in an additional 350 metric tons of high-quality algae carbon available to fuel river and riparian food webs each year (Deemer and others, 2022). These increases in GPP have been linked to higher growth rates of native flannelmouth sucker (*Catostomus latipinnis*) and humpback chub (Hansen and others, 2023; Hansen and others, 2024). Bug Flows also increases growth rates and angler catch rates of rainbow trout (Metcalfe and others, 2020; Korman and others, 2022).

Additional years of Bug Flows testing in FY 2025-27 would improve our understanding of ecosystem response to these flows and relation of this flow experiment to other LTEMP goals. Bass Flows that are intended to suppress reproduction and recruitment of these invasive fish may be tested during FY 2025-27, and additional hypotheses concerning invertebrate and ecosystem response to these flows can be developed once a Record of Decision and preferred alternative is selected.

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.*

Project F also supports LTEMP goals for *Humpback Chub*, *Other Native Fishes*, *Rainbow Trout Fishery*, and *Nonnative Invasive Species* by quantifying the feeding habits of fishes (see F.4) and by monitoring invertebrate prey resources in the mainstem and tributaries (see F.1, F.2, F.3), which informs ongoing fish and bat monitoring (e.g., Korman and others, 2021; Metcalfe and others, 2023; note that bat monitoring conducted as part of F.1 is currently unfunded).

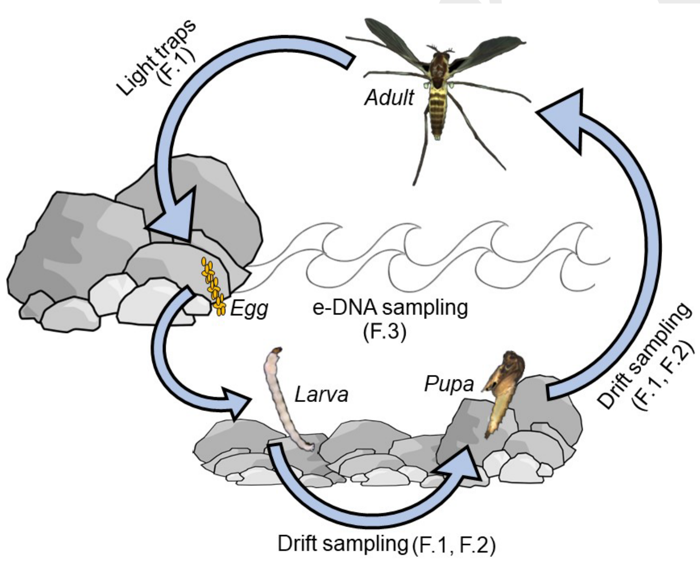

Figure 3. Typical life cycle of an aquatic insect. Non-biting midges (Chironomidae), which represent the dominant aquatic insect in the Colorado River food web, are shown. The diversity of sampling methods utilized in Project F target different life stages of insects. Aquatic insects are susceptible 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 aquatic insect egg survival.

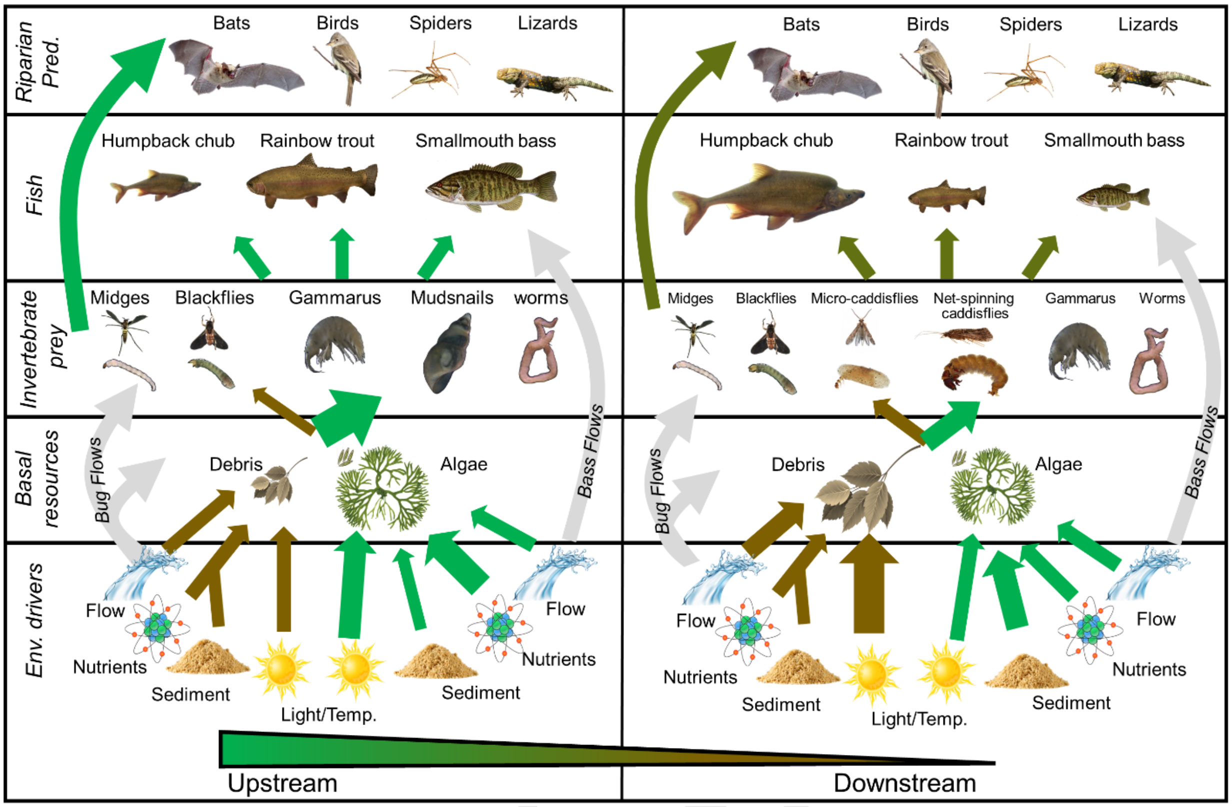

Figure 4. Simplified conceptual model of the Colorado River ecosystem. Arrows indicate linkages between food web components, with the strength of the arrow roughly indicating the strength of the linkage. Note the arrow between flow and aquatic insects, which is the linkage being tested by the Bug Flows experiment. The height of the bottom triangle indicates the amount of whole-ecosystem basal productivity (decreasing from Lees ferry to Western Grand Canyon) and the color indicates the primary source of energy (green = gross primary production; brown = detritus) fueling upper trophic levels.

Proposed Work

Project Element F.1. Aquatic Invertebrate (funded) and Bat (unfunded) Monitoring in Marble and Grand Canyons

Theodore A. Kennedy[1], Cheyenne Szydlo[1], Eric Scholl[1], Anya Metcalfe[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

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. 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). For example, invertebrate drift biomass ($g \cdot m^{-3}$) was the single-best predictor of rainbow trout growth over a 5-year study spanning 5 sampling sites and 80 river miles (Korman and others, 2021). Notably, invertebrate drift biomass was a better predictor of rainbow trout growth and survival than water temperature, turbidity, intra-specific competition, and other variables.

This project element focuses on identifying links between Glen Canyon Dam operations, environmental conditions (e.g., tributary flooding, water temperature), 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, bats, and other wildlife populations (see Projects G and H, especially).

The main thrust of F.1 is the community science monitoring of emergent aquatic insects, where river guides, education groups, private boaters, and other members of the public deploy a simple light trap each night in camp in a standardized fashion to collect samples of adult aquatic insects that have emerged from the Colorado River (Kennedy and others, 2016; Metcalfe and others, 2021). At the conclusion of their river trips, community scientists return samples to our USGS laboratory for processing. 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. Community science participants are provided a modest stipend ($20) for each light trap sample they collect to ensure high quality data.

Starting in 2017 we began partnering with community scientists to monitor bat acoustic activity in conjunction with insect monitoring. These bat monitoring data have documented 19 species of bats and shown that bat activity is strongly and positively related to the abundance of aquatic flies (Metcalfe and others, 2023). These bat activity monitors run on a tablet computer and can identify bats to species based on their calls. This bat monitoring application features an interactive display that allows the community scientist to see, in real-time, the species and numbers of bats that are active during monitoring, providing a powerful tool for outreach and education. The tablet records all this information as a sound file that is downloaded to a computer at GCMRC once the river trip has concluded.

To reduce costs, we currently propose to discontinue system-wide bat monitoring. Additionally, we propose to discontinue monitoring of invertebrate drift on annual spring river trips but will continue collecting invertebrate drift samples at the Juvenile Chub Monitoring site during those trips. The invertebrate drift data collected during Juvenile Chub Monitoring trips will be provided to Project G to inform growth and survival trends in humpback chub and other fishes.

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

Morgan Ford[1], Theodore A. Kennedy[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

This element is a continuation of a 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 (e.g., Korman and others, 2017; Korman and others, 2021). This monitoring is carried out using published methods developed by the food base group (Copp and others, 2014; Kennedy and others, 2014; Baxter and others, 2017; Muehlbauer and others, 2017).

Invertebrate drift will be sampled 4 times per year concurrent with Trout Reproduction and Growth Dynamics monitoring trips (see Project H). Sampling will occur at 5 sites distributed from Glen Canyon Dam (RM -16) to the Lees Ferry boat ramp (RM 0) using methods described in Kennedy and others (2014). In brief, drift nets are deployed from a boat in the center of the channel at a fixed depth (7 feet) using a hand-powered winch, and a 75lb sounding weight keeps the nets oriented into the current. Flow meters on the net-mouth and on the sounding weight are compared and used to verify that nets have not become clogged during the 5 minute deployment (Muehlbauer and others, 2017). Five-minute deployments typically filter ~50 m^3 of water.

The proposed study design (4 sampling bouts per year, 5 locations per bout) represents a reduction in monitoring effort to reduce costs compared to the ~monthly monitoring that has been conducted since 2007. Despite the reduction in effort, this should provide useful information on the invertebrate prey base to inform trends in rainbow trout condition, growth, and survival (see, for example, Korman and others, 2021). To further reduce costs, we also propose to discontinue sticky trap and light trap sampling of adult aquatic insects, which require an overnight stay in Lees Ferry.

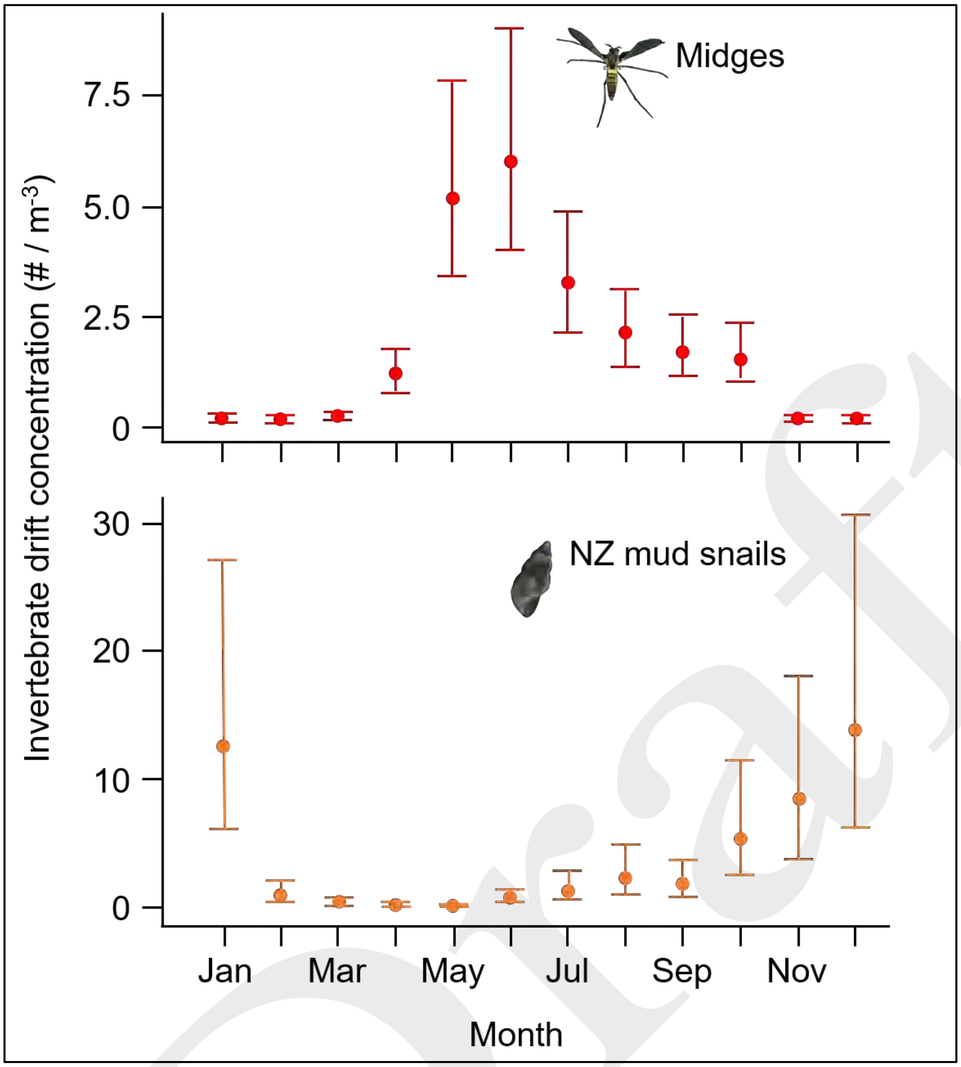

Figure 5. Drift concentrations (#/m^3) of midges and New Zealand mud snails from Glen Canyon monthly monitoring. Points represent the mean +/- one standard error estimated from a mixed-effects model. Period of record is 2007-2022. Note the seasonal differences, with more midge activity in summer months and more mud snail activity in the winter.

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

Theodore A. Kennedy[1], David Lytle[2]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Department of Integrative Biology, Oregon State University

This element involves monitoring the aquatic invertebrate community within tributaries and the mainstem in Grand Canyon using eDNA. All organisms that are living in a stream or river shed DNA. By filtering water samples from different water bodies and extracting the DNA from these samples, we can obtain a record of the communities of invertebrates, algae, parasites, fishes, and other organisms that are present.

eDNA monitoring of tributary streams is relevant to management, because these streams are important spawning and rearing habitat for native fishes, and some are also sites of humpback chub translocations. For this reason, understanding the diversity of aquatic food base resources available to these fishes can influence decisions about whether to translocate more fishes into these streams, and in identifying candidate streams for future translocations. Further, tributaries represent sources of aquatic insects that could recolonize the mainstem Colorado River. Understanding the locations of these aquatic insect populations therefore provides insight into where we might first expect to see sensitive Ephemeroptera (mayfly), Plecoptera (stonefly) and Trichoptera (caddisfly) taxa colonizing the mainstem.

Water samples for eDNA analysis of invertebrate diversity have been collected annually on April food base monitoring river trips starting in 2021 and processed and analyzed by cooperators at Oregon State University. Sample collection entails filtering four, 1-liter replicates of water per sampling location onto 0.4 um filters and preserving the filter in a buffer. Sampling locations include major tributaries in Grand Canyon (n= 18) and the mainstem Colorado River just upstream of these tributary confluences. In the laboratory, analysis of eDNA water samples entails amplifying a 142 base pair fragment of the mitochondrially encoded cytochrome c oxidase I gene (COI) with a degenerate primer set that targets aquatic invertebrates (Leese and others, 2021). These are then sequence using an Illumina Miseq platform and sequences are filtered and identified to species (technically, operational taxonomic units or OTUs) using the R package JAMP. We have been collaborating with USGS Arizona Water Science Center Staff on April river trips since 2022 to collect detailed water quality information (e.g., anions, cations, nutrients, trace metals, pH, discharge, etc.) on tributaries and mainstem locations to inform invertebrate community analyses derived from eDNA sampling.

eDNA monitoring demonstrates that tributaries in Grand Canyon support more diverse invertebrate communities compared to the mainstem Colorado River, with considerable variation in invertebrate communities across tributaries and very little variation in communities across 280 miles of the mainstem (Figure 6; Lytle and others, 2023). Notably, eDNA monitoring of invertebrate diversity in tributaries has documented twice the number of invertebrate genera compared to traditional benthic surveys of invertebrates (e.g., Oberlin and others, 1999). Specifically, Oberlin and others (1999) documented 42 genera of invertebrates across 10 tributaries while eDNA monitoring has documented 84 invertebrate genera across 18 tributaries. Using funding from a 3-year USGS/NPS-Water Quality Partnership grant awarded to Theodore Kennedy (USGS), Emily Omana-Smith (NPS) and David Lytle (Oregon State University), DNA that has been extracted from water samples is also being amplified and sequenced using other primer sets that are specific to metazoans to detect parasite and pathogen communities in tributaries and the mainstem. Archived eDNA water samples dating back to 2021 and new samples that will be collected during FY 2025-27 can also be used to detect the presence/absence of nonnative invertebrates, parasites, pathogens, and fishes whose ranges and distribution are expanding or contracting.

The cooperative agreement associated with F.3 to Oregon State University will fund a new PhD student to perform DNA extractions on new samples and model the distribution and potential expansion of parasites, invertebrates, and fish using these eDNA water sampling data.

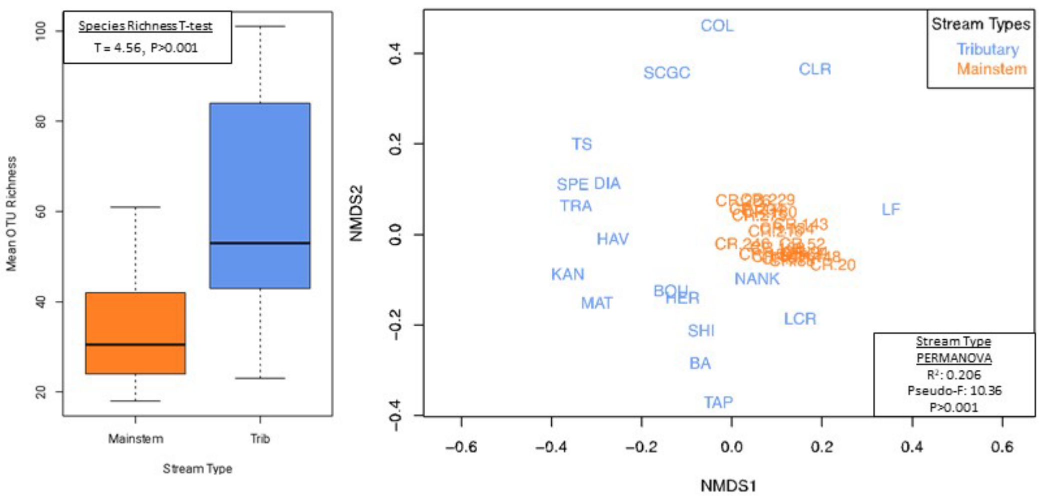

Figure 6. Box-plot (left panel) and non-metric multidimensional scaling plot (NMDS; right panel) of eDNA monitoring results from the mainstem Colorado River and tributaries in Grand Canyon. The box plot shows the mean number of operational taxonomic units (OTUs, which are equivalent to species) detected at each of 18 mainstem sampling locations and 18 tributaries. The NMDS plots depicts the variation in species composition of invertebrates detected in each tributary (BLUE) and the mainstem (ORANGE). Note the large amount of variation in invertebrate community composition across tributaries and the minimal variation in invertebrate community composition across 18 mainstem sites. Figure courtesy of David Lytle, Oregon State University.

Project Element F.4. Fish Diet and Health Studies

Theodore A. Kennedy[1], David Lytle[2], Kathrine Behn[1], Eric Scholl[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Department of Integrative Biology, Oregon State University

Current food base monitoring approaches were informed by detailed food web studies and invertebrate 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 turbid 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; Deemer and others, 2022). 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 overall 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 community science light trapping of the understudied adult life stage of aquatic insects (Kennedy and others, 2016).

Owing to numerous changes in the food base and fish communities since the last detailed food web studies ~15 years ago, we will assess feeding habits of flannelmouth sucker, humpback chub, rainbow trout, and smallmouth bass. We will focus on non-lethal methods in line with tribal concerns regarding the taking of life. Specifically, we will collect fin clips from fishes to analyze for stable isotopes and we will collect fecal samples for DNA 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 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 more detailed snapshot of feeding habits that we will obtain from DNA analysis of fish feces. DNA analysis of fish fecal samples will be done at Oregon State University using the same laboratory processing as described above for eDNA water sampling in F.3; interpretation and analysis of these fecal DNA data will be done by USGS staff. Using funding from a USGS/NPS-Water Quality Partnership grant, we are supporting a PhD student to analyze fish fecal samples for parasites and pathogens to provide baseline information on these communities. Changes in water quality associated with aridification and declining elevations in Lake Powell reservoir are changing the environment for, and risks associated with, parasites and pathogens. Additionally, increases in fish passage through Glen Canyon Dam associated with declining reservoir elevations are introducing new species of fish and their parasites to the CRe. Feeding habits of smallmouth bass that are euthanized as part of ongoing removal efforts will be accomplished using traditional gut content analysis.

Outcomes and Products

Project F will evaluate invertebrate and food web response to changing environmental conditions and LTEMP flow experiments. Each of the four project elements will result in peer-reviewed journal articles and presentations at scientific meetings. We will also provide summaries of key food base monitoring metrics (e.g., light trap catches, EPT abundance, drift in Lees Ferry) at the GCDAMP Annual Reporting Meeting held each January.

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Budget

Fiscal Year 2025									
Project F Aquatic Invertebrate Ecology	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
F.1. Invertebrate and bat monitoring in Marble and Grand Canyons	$255,416	$4,000	$36,000	$0	$0	$0	$64,401	**$359,816**	
F.2. Aquatic invertebrate monitoring in Glen Canyon	$173,361	$4,000	$3,000	$875	$0	$0	$39,509	**$220,746**	
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$23,189	$2,000	$0	$14,436	$45,825	$0	$10,013	**$95,463**	
F.4. Invertebrate and fish diet studies	$86,626	$2,000	$1,500	$14,436	$0	$0	$22,795	**$127,357**	
Total Project F	**$538,592**	**$12,000**	**$40,500**	**$29,747**	**$45,825**	**$0**	**$136,718**	**$803,382**	**$64,752**

Project F Aquatic Invertebrate Ecology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
Fiscal Year 2026									
							22.60%		Est Full Rate = 55.5%
F.1. Invertebrate and bat monitoring in Marble and Grand Canyons	$246,606	$4,250	$42,000	$0	$0	$0	$66,185	**$359,041**	
F.2. Aquatic invertebrate monitoring in Glen Canyon	$143,275	$3,250	$4,500	$875	$0	$0	$34,329	**$186,229**	
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$33,325	$2,250	$0	$14,741	$48,175	$0	$12,817	**$111,307**	
F.4. Invertebrate and fish diet studies	$101,334	$2,250	$2,000	$14,741	$0	$0	$27,193	**$147,518**	
Total Project F	**$524,539**	**$12,000**	**$48,500**	**$30,357**	**$48,175**	**$0**	**$140,525**	**$804,095**	**$65,213**

Project F Aquatic Invertebrate Ecology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
Fiscal Year 2027									
							23.40%		Est Full Rate = 56%
F.1. Invertebrate and bat monitoring in Marble and Grand Canyons	$252,296	$4,500	$39,000	$0	$0	$0	$69,216	**$365,012**	
F.2. Aquatic invertebrate monitoring in Glen Canyon	$163,840	$3,500	$4,500	$875	$0	$0	$40,415	**$213,131**	
F.3. Aquatic invertebrate monitoring of Grand Canyon tributaries	$26,549	$2,500	$0	$15,411	$49,350	$0	$11,884	**$105,694**	
F.4. Invertebrate and fish diet studies	$77,691	$2,500	$2,000	$15,411	$0	$0	$22,839	**$120,441**	
Total Project F	**$520,376**	**$13,000**	**$45,500**	**$31,697**	**$49,350**	**$0**	**$144,355**	**$804,278**	**$65,721**

*GCDAMP Special Rate: Rate includes current DOI preferred rate (currently 15%; subject to change) and facilities rate (will vary annually). No USGS bureau overhead is charged (unique to the GCDAMP agreement).

**USGS Contributing Funds: The amount of funds required to cover the subsidy created by the reduced burden rate (i.e., GCDAMP Special Rate). As in previous years, SBSC/GCMRC will request these funds of the USGS cost-share program. These funds are not guaranteed.

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

Investigators

Maria Dzul[1], David Ward[2], Michael Pillow[2], Pilar Rinker[2], Lindsay Hansen[1], Ben Miller[1], Kim Dibble[1], Brian Healy[1], Charles Yackulic[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2] U.S. Fish and Wildlife Service

Project Summary and Purpose

The FY 2025-27 Triennial Work Plan coincides with a period that will likely present new challenges to managing fishery resources within the Colorado River ecosystem (CRe) in Grand Canyon. Most of our knowledge of humpback chub (*Gila cypha*) in Grand Canyon comes from studies that occurred under colder water conditions in the mainstem Colorado River following construction of Glen Canyon Dam. Warming of the mainstem river by a few degrees in recent years has led to large changes in fish communities in Grand Canyon (e.g., increase/expansion of humpback chub in western Grand Canyon, first observations of juvenile young-of-year [yoy] from several warm-water nonnatives) providing further evidence that water temperature is a key driver of fish communities (Lessard and Hayes, 2003; Dibble and others, 2021). The rules that will determine Lake Powell elevations and annual release volumes are unknown, and future hydrologic conditions are uncertain, making it difficult to predict how much time will be spent at lower reservoir elevations at which releases through penstocks will be as warm or warmer than releases in 2022 and 2023. Additionally, modifications to LTEMP flows are being proposed that may lead to increased frequency of spring-timed HFEs, as well as flows to disadvantage warm-water nonnatives including smallmouth bass (*Micropterus dolomieu*) that may have direct and indirect impacts on humpback chub and other native fishes. Project G is designed to estimate the effects of managed, and unmanaged, drivers on the growth, survival, and juvenile production of humpback chub to quantify impacts of management (in the context of unmanaged variation) and improve our ability to forecast future population dynamics. Project G is also designed to estimate state variables (abundance, distribution) for the 2016 Biological Opinion (U.S. Fish and Wildlife Service, 2016), and associated fieldwork and modeling efforts are supported by the 2024 Interim Guidelines Biological Opinion (U.S. Fish and Wildlife Service, 2024). Additionally, Project G includes projects to address the LTEMP Performance Metrics.

Many project elements in Project G are long-term monitoring projects to estimate humpback chub abundances at various life stages throughout different parts of Grand Canyon. In addition, monitoring from fixed sites (e.g., juvenile chub monitoring [JCM]-east, JCM-west, lower LCR) provides estimates of demographics (e.g., life-stage specific abundances) and population processes (e.g., survival, growth) which can allow us to forecast population dynamics under different management scenarios. Past data collected by these monitoring projects provide a baseline for comparison under past and future climate scenarios and can also provide information about if (how) potential increases in warm-water nonnative fishes (e.g., smallmouth bass, green sunfish [*Lepomis cyanellus*], walleye [*Sander vitreus*]) affect humpback chub population dynamics. For this reason, continuing long-term monitoring is a priority in Project G for FY 2025-27.

Additionally, monitoring outlined in Project G will help document whether high age-0 production of humpback chub in 2022 and 2023 in the Colorado River ecosystem experience resource limitation, density-dependence, and natural population fluctuations in the near future. In both JCM-east and JCM-west, monitoring efforts have documented strong cohorts (i.e., lots of age-0 fish) in 2022 and 2023, years when adult humpback chub abundances were also high. It is unknown whether juvenile humpback chub born in 2022 and 2023 will successfully recruit to the adult population, or whether resource limitation and density-dependence will cause high mortality of these fish, similar to the population decline documented for rainbow trout in 2014 and 2015 that occurred after a large production pulse in 2011. Similarly, the LCR had high production of age-0 humpback chub in spring 2023, but these fish were all of small size and it is unknown how many from this cohort will survive winter in the LCR.

In summary, Project G includes project elements to estimate abundances required by the 2016 Biological Opinion (G.1, G.2, G.3, G.4) by monitoring humpback chub in the LCR-spawning population by sampling the LCR and JCM-east reach in the Colorado River (Project Elements G.2, G.3). Additionally, this project includes sampling in western Grand Canyon via continuation of mark-recapture in the JCM-west reach (210.5-214 river miles downstream of Lee Ferry) and extensive spatial sampling via the aggregation trips (Project elements G.5, G.6). Mark-recapture data from these trips will be supplemented with data from autonomous PIT tag antennas (Project Elements G.4, G.9), such as the LCR multiplexer array and submersible antennas, as these technologies have proven effective at detecting larger adults. Data collected from the above-mentioned field efforts will be analyzed to help learn more about humpback chub life history and to guide management efforts (Project Element G.1).

Background

Humpback Chub in Grand Canyon

We distinguish three different groups of humpback chub within Grand Canyon: 1) LCR spawners, 2) mainstem spawners in western Grand Canyon (i.e., between the confluence of Havasu Creek and Pearce Ferry rapid), and 3) humpback chub in other tributaries (e.g., Havasu Creek, Shinumo Creek, Bright Angel Creek). Of these three groups, LCR-spawning humpback chub represent the most established component of the population, as this group was able to persist in relatively high abundance in Grand Canyon despite construction of Glen Canyon Dam and resulting reductions in water temperature (Wright and others, 2009).

In contrast, mainstem spawners in western Grand Canyon were rare up until 10-15 years ago, but since 2016 this group of humpback chub has become numerous and widespread throughout western Grand Canyon and represents a relatively ‘new’ component of the humpback chub population. Humpback chub in other Grand Canyon tributaries are less abundant than the other two groups and are largely the result of translocations by the National Park Service. Humpback chub in the first two groups (LCR-spawning, and western Grand Canyon mainstem-spawning) are monitored by U.S. Fish and Wildlife Service (USFWS) and U.S.G.S., whereas humpback chub in other tributaries are monitored by National Park Service (NPS) outside of the Glen Canyon Dam Adaptive Management Program (GCDAMP).

LCR-Spawning Humpback Chub (Project Elements G.1, G.2, G.3, G.4, G.7, G.8)

After closure of Glen Canyon Dam in the mid-1960s, water temperatures in the mainstem Colorado River plummeted due to hypolimnetic releases from Lake Powell (Wright and others, 2009). Lab studies confirmed that generally water temperatures in this segment of the Colorado River were too cold for successful humpback chub reproduction (Hamman, 1982; Gorman and VanHoosen, 2000; Robinson and Childs, 2001). Humpback chub were able to successfully spawn and recruit in the LCR, which had warmer water temperatures and also a more natural flood regime compared to the Colorado River mainstem (Kaeding and Zimmerman, 1983; Robinson and Childs, 2001). Humpback chub abundance in the LCR decreased in the early 2000s (Coggins, Jr. and others, 2006), prompting trout removal efforts in the mainstem near the LCR confluence from 2003-2006. Humpback chub abundances started increasing in the mid-2000s, shortly after trout removals and also during a period of warming mainstem water temperatures, leading to uncertainty about what mechanism(s) ultimately were responsible for the population rebound (Coggins, Jr. and others, 2011). Additionally, un-modeled temporary emigration led to retrospective negative bias in humpback chub abundances (Coggins, 2008), suggesting the need for a different modeling approach that included monitoring both in the LCR and mainstem Colorado River. Since the mid-2000s, adult population abundances have increased and remained above 9000 for LCR-spawning humpback chub (Dzul and others, 2022).

Ecological studies of LCR-spawning humpback chub indicated a dual life history strategy – some individuals (hereafter LCR residents) in this population never leave the LCR and others (hereafter LCR migrants) that are originally born into the LCR out-migrate to the Colorado River as juveniles or subadults and then migrate back to the LCR to spawn as adults (Yackulic and others, 2014; Dzul and others, 2021). LCR residents typically exhibit a ‘fast’ life history strategy, where they grow to adulthood within 3 years and live 1-2 years upon reaching adulthood.

In contrast, LCR migrants have slower growth due to inhabiting colder water temperatures[1], so they typically take 3-6 years to reach adulthood but have longer lifespans (typically live on ~5-8 years after reaching adulthood but can live over 30 years). Skipped spawning occurs in this population, however, incorporation of antennas into population models suggests that skipped spawning is less common than previously reported by other models (Yackulic and others, 2014; Dzul and others, 2021).

For the Bureau of Reclamation (Reclamation) to meet compliance with the Endangered Species Act, abundances of LCR-spawning humpback chub are used to evaluate the need for management actions as part of the Biological Opinion in the LTEMP ROD (U.S. Department of the Interior, 2016; U.S. Fish and Wildlife Service, 2016). Specifically, the Biological Opinion identifies three tiers for management actions based on adult abundances of > 9000 (tier-0), 7000-9000 (tier-1), and < 7000 (tier-2). Subadult abundances are also included to ensure that adult abundances are on-track to meet the threshold abundances associated with each tier. These tiers can ‘trigger’ management actions – for example, if adult humpback chub abundance is between 7000-8999, then additional management actions (namely, humpback chub translocations) are warranted and if adult abundance falls below 7000 and rainbow trout densities are moderate or high (>60 individuals per km), trout removal efforts are required. Abundance values for tier determination are estimated from Project Elements G.1, G.2, and G.3. Chute Falls translocations (G.7) represent an action that can be used to improve humpback chub abundances in tier-1, but Project Element G.7 is currently proposed as unfunded in this work plan.

The future health of the LCR-spawning population is dependent on future conditions, which are uncertain (Figure 1). Predictions of future climate suggest increased warming and more severe water shortages for the U.S. Southwest (Udall and Overpeck, 2017), leading to increased likelihood of the following stressors: 1) reduced flooding in the LCR due to heat-stressed drought (Udall and Overpeck, 2017), 2) warmer mainstem water temperatures due to lower Lake Powell water levels[2] (Dibble and others, 2021), 3) population expansion/growth of nonnative piscivorous fishes (e.g., smallmouth bass, green sunfish, walleye; Dibble and others, 2021).

[1]However, water temperatures have been warming in recent years (Dibble and others, 2021). Lake Powell reservoir levels in particular were very low in 2022, resulting in warm water temperatures and fast growth of humpback chub (Figure 3).

[2] However, note Lake Powell water levels are impacted by policy, which is uncertain after 2026.

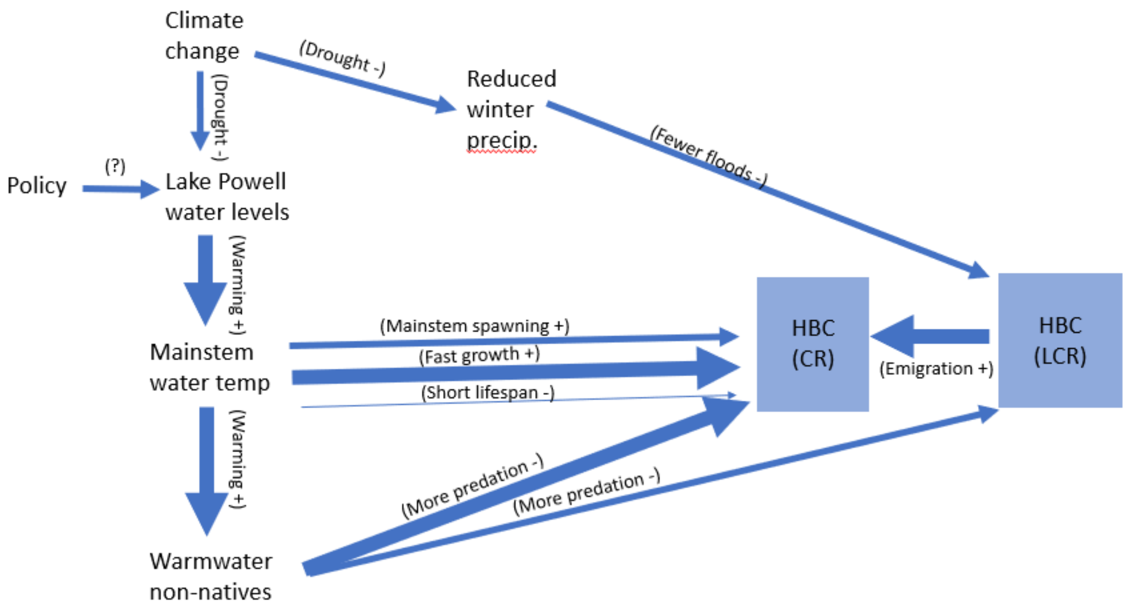

Figure 1. Conceptual model relating stressors to humpback chub (*Gila cypha*) (HBC) abundances in the Little Colorado River (LCR) and Colorado River (CR) for LCR-spawning humpback chub. Arrows represent processes and the sign in the descriptor is the hypothesized direction for the effect. The width of the arrow represents the certainty and strength of the relationship, with thick arrows representing stronger, more certain relationships than thin arrows.

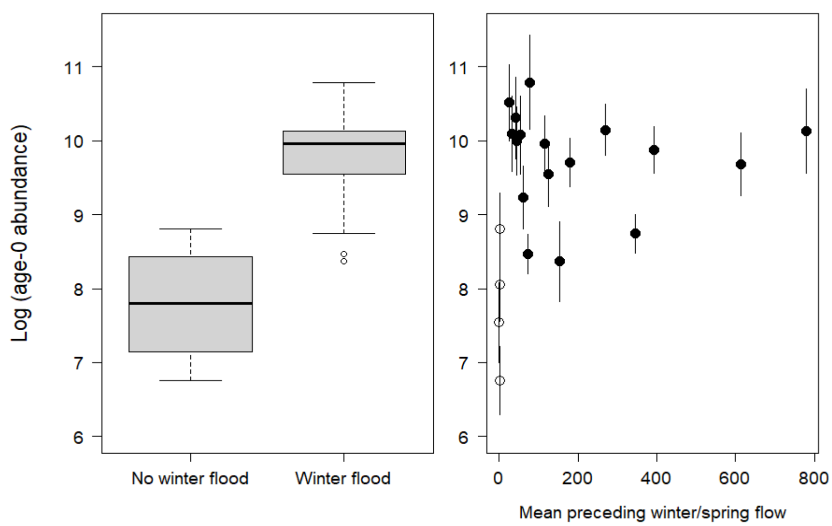

Figure 2. Log of age-0 humpback chub (*Gila cypha*) abundance in the Little Colorado River (LCR) in July plotted by years (2001-2020) with and without preceding winter floods (i.e., from 1-November to 1-April; left panel). Log of age-0 abundance in the LCR in July as a function of mean preceding winter flow (cubic feet per second - cfs) measured at the Cameron gage (USGS gage 09402000). Filled circles represent years with preceding winter floods and open points represent years without preceding winter floods. Figure from Dzul (2021).

Future climate change projections for the U.S. Southwest indicate high likelihood of heat-induced drought (Udall and Overpeck, 2017), suggesting a future with reduced river flooding, which could have negative impacts to age-0 humpback chub in the LCR. Monitoring efforts show substantial variability in age-0 humpback chub abundances from year to year (Dzul, 2021). Age-0 abundance in the LCR is low in years without preceding winter floods (Van Haverbeke and others, 2013), but even small winter floods can lead to production of large age-0 cohorts (Dzul, 2021; Figure 2). How floods affect age-0 production is unknown but could be due to factors such as siltation of gravels leading to poor egg survival, increases in nonnative fishes associated with baseflow years (Stone and others, 2018) leading to increased predation and lower survival of eggs/larvae), lack of spawning cue leading to low reproduction, or low food availability leading to poor larval survival. Thus, if the U.S. Southwest continues to incur drought, we predict that the LCR will support fewer age-0 humpback chub due to reduction in winter floods. Note, however, this prediction is uncertain because even small floods could still sustain strong age-0 production.

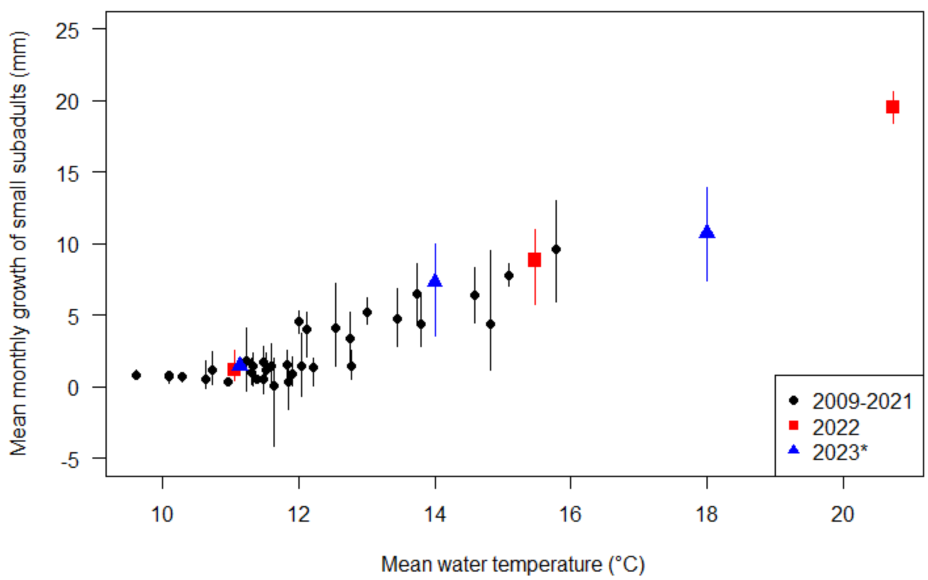

Figure 3. Observed growth of subadult humpback chub (*Gila cypha*) (starting length 100-149mm total length) captured on consecutive sampling trips as a function of mean water temperatures over that interval. Colors and shapes of points correspond to the year of the observation. *Water temperatures from 2023 were not available and were approximated.

Warmer water temperatures in the mainstem could have multiple effects on humpback chub. Growth models of humpback chub in Colorado River in Grand Canyon establish that growth is strongly influenced by temperature. In fact, in 2022, large increases in water temperature coincided with a period of much faster growth than had been observed since closure of Glen Canyon Dam (Figure 3). Increased growth in the mainstem may be beneficial to humpback chub, because fish spend less time at small size where they are more vulnerable to predation.

However, warmer water temperatures can also increase metabolic demands and oxidative stress, sometimes leading to reduced lifespan. If mainstem water temperatures are warmer in eastern Grand Canyon, we predict faster growth for LCR migrants and (possibly) reduced adult lifespan (Lee and others, 2013; Taylor and others, 2019).

Another potential effect of warming water temperatures in eastern Grand Canyon is mainstem spawning near the LCR confluence. A study of early life history humpback chub observed that survival from the egg to swim-up fry phase was ~30x greater at 16-17°C (56%) compared to 12-13°C (2%; Hamman 1982). In 2022, a year with low Lake Powell water levels, the Colorado River water temperatures near the LCR confluence (USGS gage 09383100) measured 150 days over 16°C and 92 days over 20°C, suggesting thermal conditions may be suitable for humpback chub spawning and larval development.

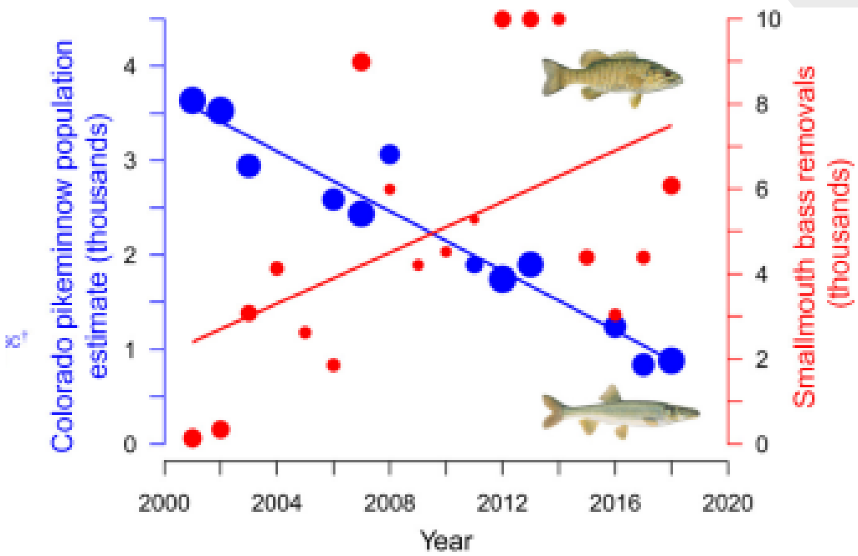

Figure 4. Relationship between estimates of Colorado pikeminnow (*Ptychocheilus lucius*) abundance and smallmouth bass (*Micropterus dolomieu*) catch (through removals). Figure from Dibble and others, 2021.

Warmer water temperatures could also lead to population growth of piscivorous, warm-water nonnative fishes, which could have negative impacts to humpback chub, as has been observed for native fish populations in the upper Colorado River basin (Dibble and others, 2021; Figure 4). Certain nonnative fishes may not be able to survive or reproduce in the LCR due to the LCR's harsh abiotic conditions (e.g., large floods, high levels of dissolved CO2; Stone and others, 2018). Thus, it is possible that humpback chub in the LCR may be less vulnerable to predation than mainstem humpback chub. However, this is highly uncertain.

In addition to emerging threats and ecosystem changes, management actions (e.g., spring HFEs to build sand bars, temperature/flow disturbances to disadvantage problematic nonnative fishes) may occur to help improve LTEMP resource goals in the Colorado River ecosystem.

The long-term record of LCR-spawning humpback chub population abundances can serve a baseline for comparing impacts of natural variability in conditions, emerging stressors, and management actions. Applying new modeling approaches to continued monitoring data will be necessary to evaluate drivers and impacts to humpback chub population dynamics. Modeling approaches will focus on linking environmental covariates (i.e., water temperature, flow, turbidity) to population processes (e.g., growth, survival).

Humpback Chub in Western Grand Canyon (Project Elements G.5, G.6, G.9)

Up until the last decade, humpback chub in western Grand Canyon were associated with two aggregation[3] sites (Colorado River near Havasu Creek and Pumpkin Spring), which were estimated to have abundances of 13 and 5 adult humpback chub, respectively (Valdez and Ryel, 1997). Starting as early as 2006, increases in catch of humpback chub were observed at aggregation sites (Persons and others, 2017), and, by 2017, humpback chub became widespread throughout the western portion of Grand Canyon downstream of the confluence with Havasu Creek (Van Haverbeke and others, 2017; Rogowski and others, 2018).

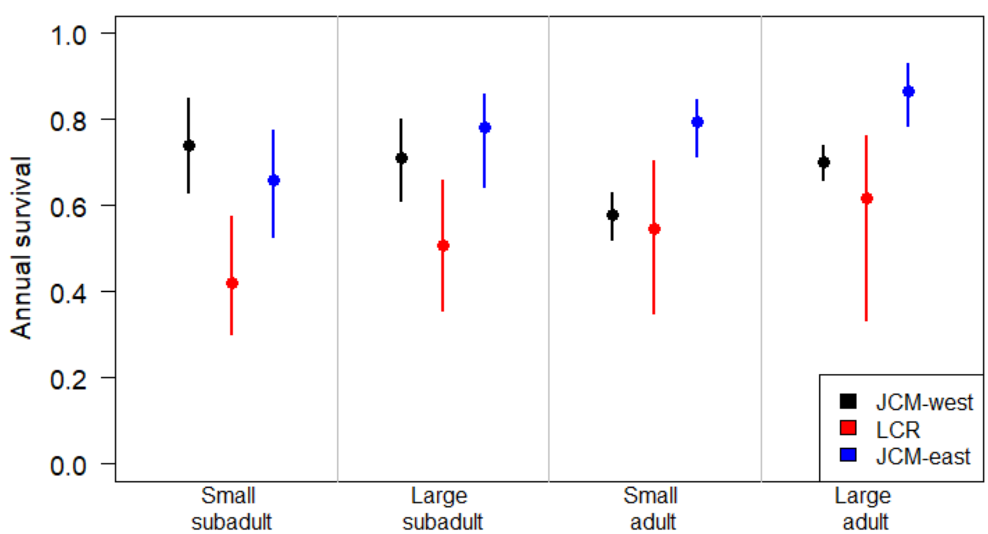

Figure 5. Graph of survival probabilities for humpback chub for different life stages (small subadult- 100-149mm TL; large subadult- 150-199mm TL, small adult- 200-249mm TL, large adult ≥250mm TL) in three different locations (LCR, JCM-east, JCM-west). Because all LCR-spawning humpback chub visit the LCR and are susceptible to capture, survival for JCM-east and LCR humpback chub corresponds to true survival. In contrast, survival in JCM-west represents apparent survival (i.e., probability fish survives and remains in the study reach) because fish can swim out of the reach and never be captured again.

[3]Aggregations were a term first used by Valdez and Ryel (1997) to describe the patchy spatial distribution of humpback chub in the Colorado River in Grand Canyon during the late 20th century. Most aggregations sites occurred in areas near sources of warm water (e.g., near the mouths or tributaries or in warm-water springs) that were interspersed throughout the river. Valdez and Ryel (1997) identify nine aggregations, but only two of these are in what is considered to be western Grand Canyon (i.e., downstream of Havasu Creek).

Ecological studies of western Grand Canyon humpback chub show this group is unique from LCR-spawners and that their life history is intermediate to that of LCR-residents and LCR-migrants on the fast-slow spectrum (Dzul and others, 2023). Specifically, western Grand Canyon chub exhibited faster growth and lower asymptotic body size compared to LCR migrants and slower growth/higher asymptotic body size compared to LCR residents. Apparent survival of subadult humpback chub in western Grand Canyon was relatively high and more comparable to that of LCR migrants (Figure 5). Taken together, the fast growth and high survival of subadults partly explains the rapid population growth observed in western Grand Canyon.

Adult apparent survival (i.e., the probability of surviving and remaining in the study reach) displayed a more tenuous pattern because, unlike both LCR migrants and LCR residents, apparent survival in western Grand Canyon did not increase with fish size (Dzul and others, 2023; Figure 5). Adult apparent survival in western Grand Canyon tended to be relatively low (more comparable to LCR residents), and it is unknown whether the lower observed apparent survival probability is due to high mortality or high emigration from the study area. Apparent survival probabilities were lowest in spring, a time when humpback chub are spawning. Previous movement studies of LCR-spawning and upper basin humpback chub suggest humpback chub tend to exhibit only localized movements around a small spatial area (Valdez and Ryel, 1995, Kaeding and others, 1990), though LCR-migrants did exhibit longer-distance spawning migrations into the LCR in spring (Valdez and Ryel, 1995). It is unknown whether western Grand Canyon humpback chub are more mobile compared to other populations and(or) whether this group migrates during the spawning season. To help address this question, we have introduced an antenna monitoring project that uses citizen science to spatially expand and randomize detection probability within Grand Canyon (Project Element G.9).

Hypotheses and Science Questions

1) Are LCR-spawning humpback chub increasing, decreasing, or stable?
   a. Which life history stages and demographic processes are influencing trend?
   b. Are management actions needed to increase abundances to meet compliance (i.e., triggers)?
2) Are western Grand Canyon humpback chub increasing, decreasing, or stable?
   c. Which life history stages and demographic processes are influencing trend? (requires G.6, cannot answer this question at given funding levels).
   d. Have humpback chub in western Grand Canyon reached carrying capacity? (requires G.6, cannot answer this question at given funding levels).
3) How do demographic processes compare in western Grand Canyon and LCR-spawning humpback chub? Do these groups experience different drivers and stressors? (requires G.6, cannot answer this question at given funding levels).

4) How are LCR-spawning humpback chub population dynamics[4] (i.e., survival, growth, movement, recruitment) affected by environmental factors (e.g., water temperature, turbidity, flow)?

5) What are the long-term drivers of range expansion for humpback chub?

Contingent on Future Conditions (Warmer Water Temperatures & Increased Nonnatives)

6) Do warmer water temperatures lead to mainstem spawning and range expansion into eastern Grand Canyon and Marble Canyon?

7) How are humpback chub survival and growth impacted by nonnative fishes[4] in the LCR and in eastern Grand Canyon[4]?

8) How are humpback chub population dynamics and abundances[4] in the LCR and in eastern Grand Canyon affected by management actions (e.g., spring HFEs, proposed flows for nonnative suppression)?

Proposed Work

Project Element G.1. Humpback Chub Population Monitoring

Maria Dzul[1], Lindsay Hansen[1], Ben Miller[1], Brian Healy[1], Kim Dibble[1], Charles B. Yackulic[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Evaluate Population Dynamics Using Mark-Recapture Data

We will develop and refine models using data from existing (and ongoing) field sampling to help inform management efforts and conservation actions for humpback chub. Proposed foci for modeling efforts include 1) estimating abundance of various size classes in the LCR-spawning population as defined in the 2016 Biological Opinion (e.g., Figure 6; U.S. Fish and Wildlife Service, 2016), 2) developing an occupancy model that accounts for detection probability to look at long-term, large-scale changes to humpback chub distribution with the Colorado River ecosystem, 3) including antenna detections from a wide geographic area in Grand Canyon to obtain a better estimate of adult survival in JCM-west (i.e., to differentiate emigration from mortality), 4) estimate abundance of humpback chub adults in western Grand Canyon based on data collected by humpback chub aggregations sampling trips, 5) estimate the effects of environmental covariates on demographic parameters (e.g., survival, growth, movement), which may help predict humpback chub responses to management actions and future scenarios.

[4]Cannot be answered for western Grand Canyon humpback chub without Project Element G.6.

Additionally, these models will help support LTEMP Performance Metrics defined for humpback chub, including: 1) the current tier for LCR-spawning humpback chub in the 2016 Biological Opinion, 2) an estimate of humpback chub abundances across all Grand Canyon, and 3) detection/non-detection (or presence/absence) of different life stages of humpback chub across Grand Canyon.

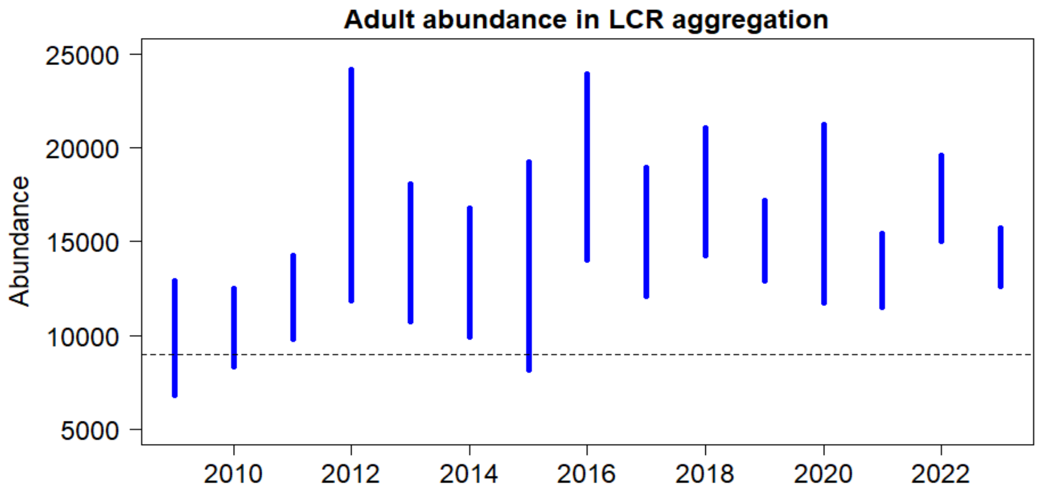

Figure 6. Estimates of adult humpback chub (*Gila cypha*) (≥200 mm total length) abundance for LCR-spawning humpback chub used for reporting for the LTEMP Biological Opinion (U.S. Department of the Interior, 2016; U.S. Fish and Wildlife Service, 2016). Bars represent 95% credible intervals.

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

Michael Pillow[1], David Ward[1], Pilar Rinker[1]

[1]U.S. Fish and Wildlife Service

USFWS Sampling Trips

The USFWS has been conducting four sampling trips into the LCR each year since 2001, and this data set is used to estimate humpback chub abundance at different life stages. These abundance estimates document substantial temporal changes to adult population size since 2000, most notable of which is the increase in adult abundance that has occurred since 2007. While all four trips sample all life stages, spring trips generally inform adult (Figure 7), large subadult, and age-1 abundance estimates in the LCR, as well as provide information about the migratory component of LCR-spawners, whereas the fall trips provide estimates of age-0 abundances in the LCR and abundances of LCR residents (Van Haverbeke and others, 2013).

Spring LCR trips generally are the best opportunity for capturing (and issuing tags to) adult humpback chub, because capture probabilities for hoop nets are higher for adults in the LCR compared to the mainstem.

Data from this project element are used to:

1) Determine length stratified estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm TL; Figure 7) in the lower 13.6 km of the LCR during the spring and fall – LTEMP Biological Opinion 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, ~2,700 PIT tags are implanted into humpback chub per year on LCR spring and fall trips (unpublished data).
4) Collect additional data on fishes in the LCR such as size, species, sexual condition and characteristics, and external parasites (i.e., *Lernaea cyprinacea*).
5) Mark-recapture data from these trips is used in a multistate model that evaluates movement between the LCR and Colorado River and generates abundance estimates for all LCR-spawning humpback chub in both rivers (Yackulic and others, 2014; Dzul and others, 2022). Data on abundance estimates is used by other agencies to address abundance thresholds associated with management triggers in the LTEMP Biological Opinion (U.S. Fish and Wildlife Service, 2016, 2024).

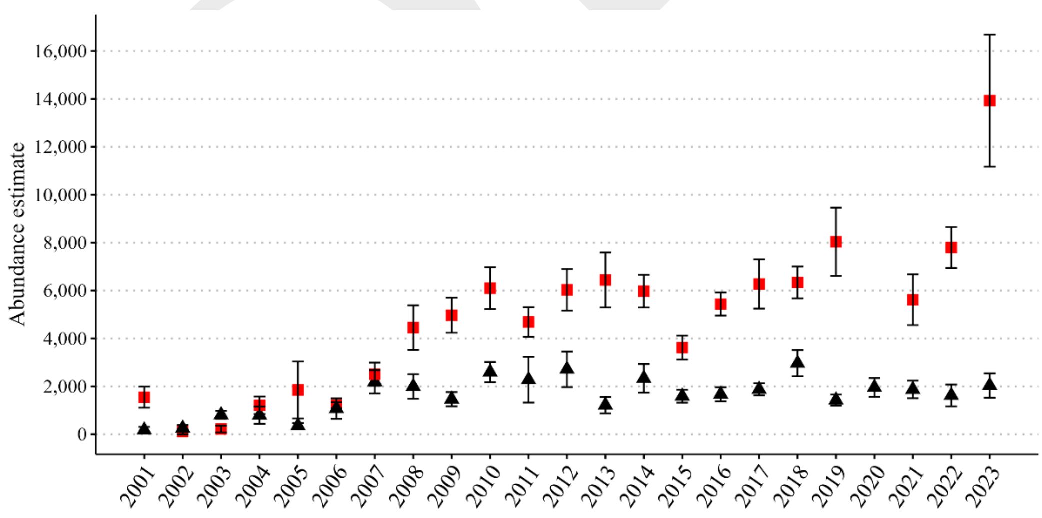

Figure 7. Spring (red squares) and fall (blue triangles) abundance estimates of adult humpback chub (*Gila cypha*) (≥200mm total length) in the Little Colorado River (LCR) from U.S. Fish and Wildlife Service lower LCR monitoring trips.

Due to limited funding, we have proposed to eliminate one trip (September) from lower LCR monitoring in FY 2027. Eliminating the September trip will impact precision of USFWS fall age-0 abundance estimates and fall adult abundances (i.e., LCR resident abundances). Additionally, eliminating this trip may also lead to lower precision for LCR-spawning adult abundances reported as part of the Biological Opinion (U.S. Fish and Wildlife Service, 2016) and lower the number of PIT tags issued to fishes.

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

Lindsay Hansen[1], Ben Miller[1], Maria Dzul[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Sampling Trips to the JCM-East Reach and Lower LCR

This project element is a continuation of previous monitoring work that commenced in 2012 and includes three annual sampling trips to the JCM-east reach (located 62.7-66.0 river miles downstream of Lees Ferry) as well as one annual sampling trip to the lower LCR (July) to estimate abundance and outmigration of age-0 humpback chub born the previous spring. Because these trips visit fixed sites and use mark-recapture methods, this project element provides information about demographic processes, such as survival and growth (Dzul and others, 2016, Dzul and others, 2023) as well as abundances (Dzul and others, 2022). The relatively long-term data set from Project Elements G.2 (25 years) and G.3 (16 years) provides baseline data about population dynamics, which can serve to help compare how future changes to the CRe (e.g., increased water temperatures, more warm-water nonnative fishes) may affect humpback chub population dynamics.

1) Data informs the multistate model (Yackulic and others, 2014, 2020; Dzul and others, 2022), which generates abundance estimates for the humpback chub adult LCR aggregation and informs triggers associated with the Biological Opinion (U.S. Fish and Wildlife Service, 2016, 2024).
2) Data informs estimates of rainbow trout and brown trout abundance near the LCR confluence (Yackulic and others, 2018), to continue to track the relationship between rainbow trout and brown trout production in Lees Ferry and abundances near the LCR. Abundances could also be estimated for other nonnative fishes, if the trip is allowed to mark and release instead of sacrificing and if nonnatives are not rare.
3) Estimate age-0 humpback chub production and outmigration, which are highly variable from year to year. Juvenile/age-0 humpback chub are the most likely life history stage to be affected by management actions and stressors (e.g., nonnative fish predation; Yackulic and others, 2018), and may provide early warnings of adult population decline.

4) Evaluate spawning dynamics (e.g., skipped spawning) and alternate life history strategies in adult humpback chub (Dzul and others, 2021).

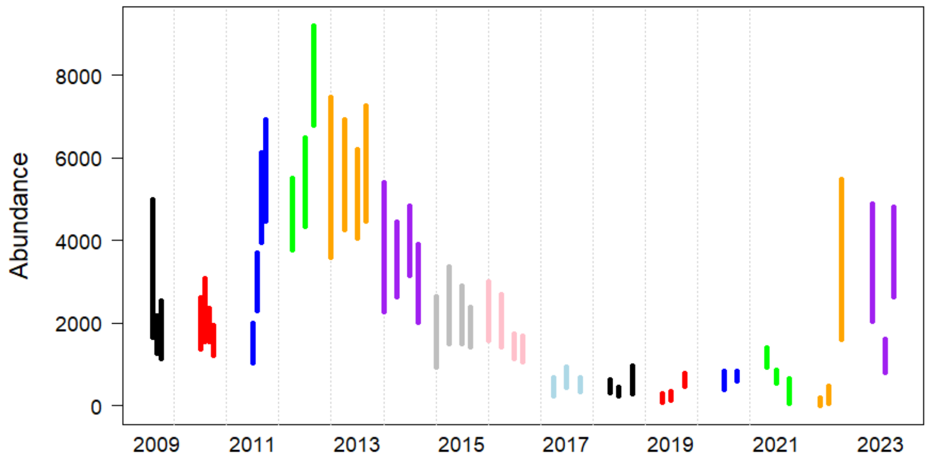

Figure 8. Abundance estimates of juvenile (<100mm TL) humpback chub (*Gila cypha*) in JCM-east sampling reach in the Colorado River. Bars correspond to 95% credible intervals.

In reference to the third focus (juvenile/subadult partial migration), previous work has suggested substantial variability in age-0 humpback chub production and outmigration from the LCR to the CR (Yackulic and others, 2014; Dzul 2021; Figure 8). The July LCR trip focuses on estimating abundances of age-0 fish that were born the preceding spring, to learn more about variability in age-0 production across years in the LCR. The mainstem JCM trips can recapture fishes marked in the LCR and provide information about outmigration probability and abundance of juveniles/subadults in the Colorado River (i.e., that will become LCR migrants as adults). Because most (~80%) LCR-spawning adults are migratory (i.e., move between the Colorado River and LCR), understanding the key drivers and natural variability in recruitment and partial migration can help generate predictive models for humpback chub that spawn in the LCR. If the Colorado River experiences more warming in the future, it is possible that some humpback chub in the Colorado River near the LCR confluence may start reproducing in the mainstem, and Project Element G.3 may help inform whether or not this occurs.

The fourth focus (estimating skipped-spawning) addresses the short-coming of earlier models (Coggins, 2008) that exhibited retrospective biases in humpback chub abundances, likely due to relying solely on LCR monitoring and not accounting for the possibility that some adults may not visit the LCR every year to spawn. Additionally, if the Colorado River warms, it is possible that more mainstem spawning may occur, so that some adults may never visit the LCR and would be missed by LCR sampling efforts.

We propose to retain the same amount of effort in FY 2025-27 as in the FY 2021-23 work plan, 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 to target small, age-0 humpback chub.

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

Maria Dzul[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Assessing Humpback Chub Movement and Improving Detection of Large Fish

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 (Figure 9). Importantly, these systems are particularly useful for detecting large (>250 mm TL) humpback chub which are difficult to capture using hoop nets (Dzul and others, 2021, 2024). In the LCR, 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 (Dzul and others, 2021). 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 (Figure 9), but rather their ability to increase detection of a subset of the humpback chub population that is relatively invulnerable to capture.

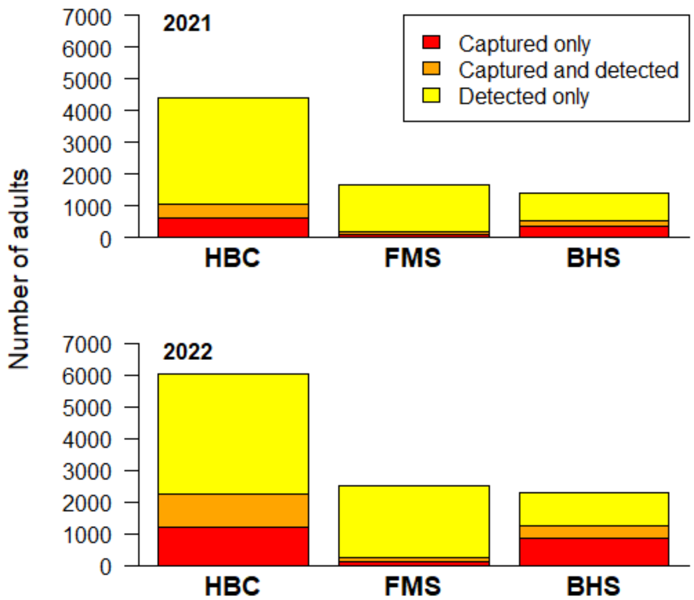

Figure 9. Comparison of adult humpback chub (*Gila cypha* - HBC), flannelmouth sucker (*Catostomus latipnnis* - FMS) and bluehead sucker (*Catostomus discobolus* - BHS) that were only physically captured (red), physically captured and detected on the MUX (orange), and only detected on the MUX (yellow) during spring of 2021 and 2022. Figure from Dzul and others (2024).

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 NET system (described in FY 2021-23 TWP) is being discontinued due to redundancy with the MUX and funding limitations. The MUX provides detection coverage across the entire channel across two arrays (downstream and upstream arrays) to inform movement directionality. The MUX is located in the LCR, ~1.8 river km upstream of the confluence with the Colorado River and was initially installed in 2009 and 2011 but replaced with an improved system in 2020. Maintenance and installation of the MUX has been funded by Reclamation outside of GCDAMP, however, GCDAMP funding is requested because USGS staff are asked to help with minor repairs, setting up trip logistics for maintenance trips, and assisting on maintenance/repair visits. Additionally, there are some USGS salary costs associated with data management and modeling antenna detection to improve population models for humpback chub and other native fishes. The MUX can also be used to detect movement of nonnative fishes that are tagged (e.g., rainbow trout, channel catfish) to determine whether or not nonnative species can persist in the LCR (Dzul and others, 2018).

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

Pilar Rinker[1], David Ward[1], Michael Pillow[1]

[1]U.S. Fish and Wildlife Service

Canyon-wide Sampling of Fish throughout Grand Canyon with an Emphasis on Humpback Chub

Aggregations of humpback chub in Grand Canyon are biologically important because they provide redundancy and resiliency for the species. 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 Biological Opinion (U.S. Fish and Wildlife Service, 2016). 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. Aggregations monitoring obtains catch information for numerous reaches throughout Grand Canyon using baited hoop nets, then periodically re-visits some sites a few weeks later to re-sample and obtain capture probability estimates. Once a range of capture probabilities are observed, models can generate abundances (Figure 10). Additionally, habitat and spatial information are used in models to help account for non-random sampling and spatial effects.

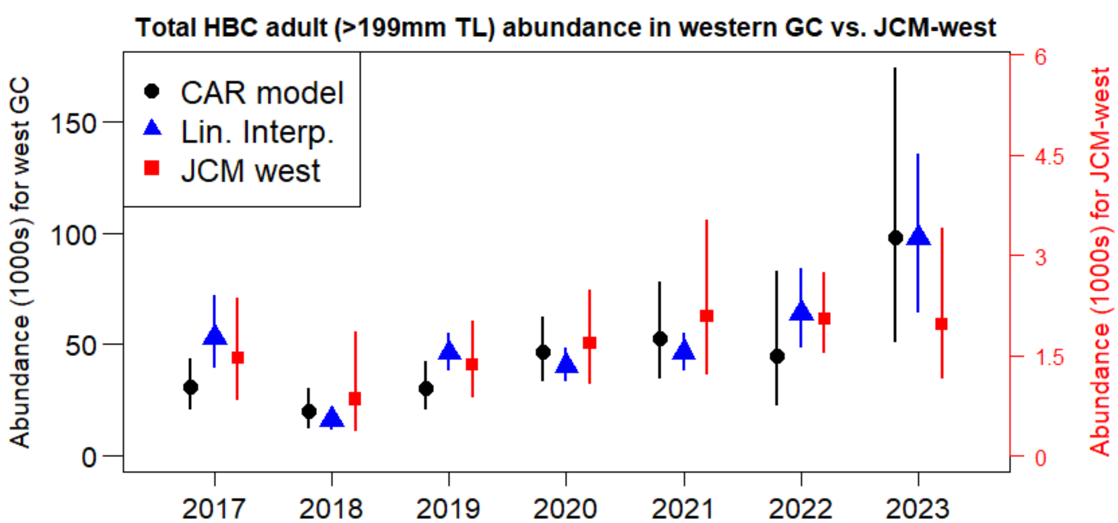

Figure 10. Abundances of humpback chub in western Grand Canyon (157-280 river miles downstream of Lees Ferry) as estimated by conditional auto-regressive models (CAR) and models with linear interpolation (Lin. Interp.). Additionally, abundances of humpback chub (*Gila cypha*) in JCM-west are modeled (left axis) to evaluate differences in trend across sites and sampling efforts.

This project will conduct one mainstem sampling trip per year focused on 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) as well as other sites that are targeted for biological interest.

Project Element G.5 funds an additional boat that can be used to seine backwaters to monitor juvenile humpback chub and warm-water nonnatives (funded in FY 2025, not funded in FY 2026 and FY 2027). One partial trip (launching and Diamond Creek and taking out at Pearce Ferry) was requested in FY 2026 but remains unfunded. This will limit the ability for the aggregations trip to learn more about capture probabilities for humpback chub, especially if water temperature warm in future years, as many of the capture probabilities from the aggregations trip comes from years with cooler water temperatures.

Project Element G.6. Juvenile Humpback Chub Monitoring – West

Lindsay Hansen[1], Ben Miller[1], Maria Dzul[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Sampling Fish in Fall Canyon Reach to Learn More About Survival, Abundance, and Growth

Humpback chub in western Grand Canyon have increased dramatically in the last 5-10 years (Van Haverbeke and others, 2017) and JCM-west monitoring was established to determine how survival, growth, abundance, and recruitment differs for this relatively 'new' group compared to the more established group of LCR-spawning humpback chub. Understanding the drivers of this population was a goal identified in the Conservation Measures of the Biological Opinion. Furthermore, the 2016 fisheries PEP specifically recommended additional study in the lower part of the CRe. To address these goals, monitoring of the JCM-west reach (i.e., in Fall Canyon, located 210.5-214.0 river miles downstream of Lees Ferry) commenced in fall 2017 and continued through 2024. Based on mark-recapture data from JCM-west, Dzul and others (2023) found different patterns in life-stage specific survival and growth rates compared to eastern Grand Canyon humpback chub (Figure 5, Figure 11) and may experience less temperature and food limitation than LCR-migrants and LCR-residents, respectively. Because humpback chub in JCM-west experience warmer water temperatures than humpback chub in JCM-east, and because water temperatures may warm in the future due to drought and low water levels in Lake Powell, humpback chub in JCM-west may serve as a predictor for changes that may occur to mainstem humpback chub near the LCR confluence.

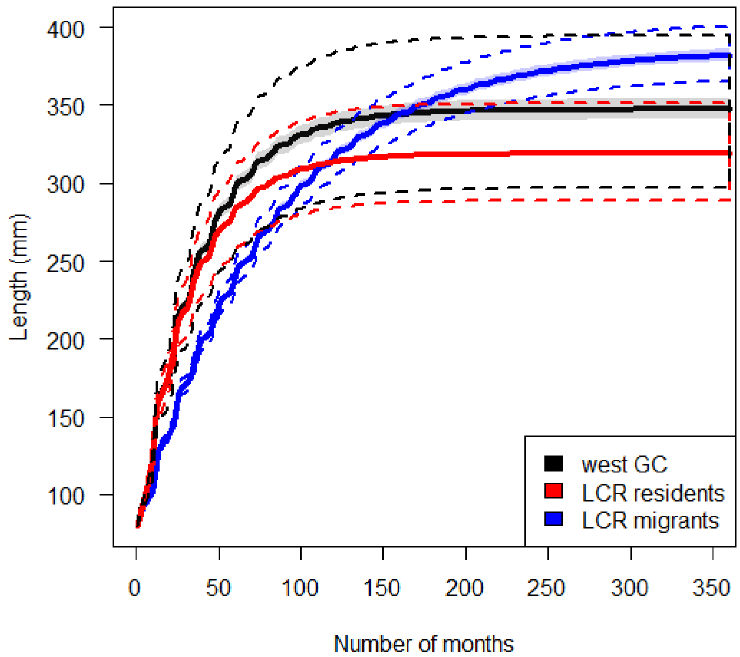

Figure 11. Growth curves for three groups of humpback chub (*Gila cypha*): Little Colorado River (LCR) residents (which spend their entire life in the LCR), LCR migrants (which migrate between the LCR and the main-stem Colorado River), and western Grand Canyon. The solid lines represent growth based on mean asymptotic length (L_∞), the shaded polygon represents 95% credible intervals for uncertainty in mean asymptotic length, and the dotted lines represent 2.5% and 97.5% quantiles for estimated asymptotic lengths across individuals. Graph is from Dzul and others (2023).

In FY 2025-27, we proposed sampling of JCM-west reach occur during the same trips (i.e., May, June/July, October) and using the same sampling methods as in JCM-east (Project Element G.3). Due to funding limitations, monitoring of JCM-west is unfunded in this work plan, so monitoring trips will only visit JCM-east and most personnel will hike out of the Bright Angel trail (except for the July trip, when everyone will run out to Diamond Creek). Due to JCM-west currently proposed as unfunded, inferences about how management actions, nonnative species, and other stressors affect survival and growth of humpback chub will mainly be limited to studies of LCR-spawners.

Project Element G.7. Chute Falls Translocations

Michael Pillow[1], David Ward[1], Pilar Rinker[1]

[1]U.S. Fish and Wildlife Service

Management (and Monitoring) to Increase Humpback Chub Adult Abundance in the LCR-Spawning Population

Translocation and monitoring of humpback chub upstream of Chute Falls has been in place as a conservation action in Biological Opinions since 2002 (U.S. Fish and Wildlife Service, 2016, 2002). To date, over 4500 juvenile humpback chub have been translocated upstream of Chute Falls. Models suggest that humpback chub translocated above Chute Falls experience fast growth and high survival and that Chute Falls translocations are a beneficial (but limited) management tool for increasing abundance of humpback chub that can be used instead of nonnative removals in certain situations (Yackulic and others, 2021; Figure 12). In recent years (i.e., 2019, 2022) biologists have documented numerous unmarked subadult humpback chub, indicating that humpback chub may be spawning and recruiting above Chute Falls, potentially increasing the benefit of this management action.

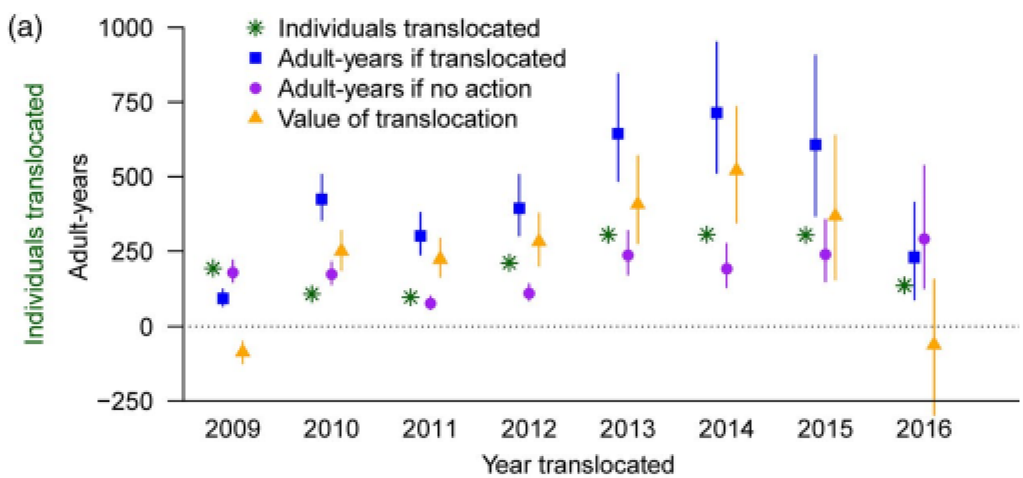

Figure 12. Population consequences of humpback chub (*Gila cypha*) translocations from individual years. The value of translocations (orange triangles) was calculated as the difference between the expected number of adult-years after translocation (blue squares) and the expected number of adult-years if translocation had not occurred (purple circles) and varies in part based on the number of chub translocated (green asterisks). Figure from Yackulic and others (2021).

In conjunction with translocation activities of humpback chub upstream of Chute Falls, this project element supports work with the USFWS Southwest Native Aquatic Resources and Recovery Center at Dexter, NM to maintain a long-term genetic refuge of humpback chub.

Additionally, humpback chub collected from the LCR by this effort have been used by NPS to provide juvenile humpback chub for translocation activities into Shinumo Creek and Havasu Creek.

Funding is used to support one additional camp (3-4 people) during the May USFWS sampling trip for monitoring work, and additional people and helicopter time during the October trip to catch and translocate fish from the lower LCR to above Chute Falls. This project element is currently proposed as unfunded in this work plan.

Project Element G.8. Sampling of Springs in the Upper LCR

David Ward[1]

[1]U.S. Fish and Wildlife Service

Sampling of the Upper LCR (~32 River Kilometers from Confluence) for Humpback Chub

In the past, fish monitoring of the LCR has focused primarily on areas where humpback chub are known to occur (i.e., downstream of Blue Springs, located 21 rkm above the confluence with the Colorado River), with upstream sections less frequently monitored. Above Blue Springs, flow in the LCR is intermittent until reaching the White Mountains, near the headwaters of the LCR. When the LCR is not flooding, this intermittent section of the LCR is comprised of numerous springs interspersed through patches of dry riverbed, and when floods occur, the increased flow coming down the LCR corridor connects this intermittent segment to the rest of the LCR. This intermittent habitat has been recognized as a potential source of nonnative species getting washed downstream from the upper LCR but it has not been considered to be suitable habitat for native fishes moving upstream from Blue Springs. Accordingly, biologists from USFWS were surprised to capture both juvenile and adult humpback chub in this stretch of river (~rkm 32.5) as part of their nonnative fish surveys in June 2023 (funded in Project I in the FY 2021-23 TWP).

The LCR experienced large floods during the winter of 2022-2023, and it is unknown whether humpback chub found in the upper LCR in June 2023 were recent migrants from the lower reaches (i.e., swam up from the lower LCR during the 2023 flood), or whether humpback chub have persisted in these spring habitats for numerous years. Furthermore, if humpback chub are recent transplants, it is unknown how long can they persist/reproduce in these patchy spring habitats or whether these fish are likely to die shortly after upstream movement and subsequent isolation. This project aims to understand habitat use and movement dynamics of humpback chub in the upper LCR, and will help evaluate: 1) to what extent (if any) LCR population estimates of humpback chub are biased due to restricted spatial sampling (i.e., lower LCR only), 2) whether movement into the upper LCR acts as a source of mortality for adult HBC in flood years (i.e., adults swim up, get stranded in springs, and eventually die), and 3) whether upstream springs can act as refugia for humpback chub if the mainstem Colorado River warms is invaded by nonnative warm-water piscivores (e.g., smallmouth bass, walleye, green sunfish) that may threaten recovery. Additionally, fish surveys of the upper LCR would continue to help biologists evaluate to what extent these springs act as sources of nonnative fishes that can seed the lower LCR during floods.

Initially, we proposed (2) 5-day trips to the upper LCR in FY 2025 (1 in spring, 1 in fall) to evaluate the spatial distribution of humpback chub and other fishes in the intermittent flow habitats of the upper LCR. Collection of eDNA samples would supplement physical capture data. This project element is currently proposed as unfunded in this work plan.

Project Element G.9. Movement in Western Grand Canyon from System-Wide Antenna Monitoring

Eric Frye[1], Maria Dzul[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Increase Use of Submersible Antennas throughout Grand Canyon to Detect Fishes in Less-Frequently Sampled River Reaches

Because the Colorado River in Grand Canyon cannot be sampled in its entirety, biologists must frequently make assumptions about fish movement in order to fit population models to estimate abundance and survival. Often, movement out of a study site (i.e., permanent emigration) is confounded with mortality so that biologists can only obtain estimates of 'apparent' survival (i.e., probability a fish survives and remains in the study site). Apparent survival estimates of fishes in JCM-west are relatively low for adult humpback chub, suggesting either increased emigration or increased mortality of adult humpback chub in western Grand Canyon compared to near the LCR. Estimates of apparent survival can impair population inference, because movement and mortality have different implications for population dynamics. By searching for marked fishes in river reaches that are less frequently visited by fish monitoring trips, biologists would learn more about fish movement patterns and this updated information could be used to improve population models.

We propose purchasing 8-10 submersible antennas that could be deployed on numerous scientific trips (e.g., Arizona Game and Fish system-wide electrofishing trips that randomly sample reaches) and 4-5 submersible antennas that could be deployed by river boatmen as part of a citizen science project to help collect data about movement of fishes. These antennas would be baited, deployed overnight throughout a section of river, and collected the following morning. Citizen scientists would be paid for data collection (fee TBD, ~$40). Due to funding shortages, this project element is currently proposed to be funded only in FY 2025.

Outcomes and Products

The work described here will lead to multiple peer-reviewed publications. In particular, we expect 1 or more manuscripts describing abundances in western Grand Canyon, 1 or more manuscripts evaluating the effects of environmental covariates on demographic processes in eastern and western Grand Canyon, and 1 or more manuscripts assessing changes in the longitudinal distribution of humpback chub in Grand Canyon over the last few decades. We will continue to provide annual summaries of life-stage specific abundances and demographic processes that serve as triggers for management actions in the 2016 Biological Opinion (e.g., abundance, survival, recruitment, and growth rates; U.S. Fish and Wildlife Service, 2016) at the GCDAMP Annual Reporting Meeting each January and continue to develop predictive models that have served as decision support tools for the LTEMP EIS and post-2016 guidelines. Also, we will provide more frequent summaries of some LTEMP Performance 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.

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Budget

Fiscal Year 2025									
Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
G.1. Humpback chub population modeling	$148,527	$8,000	$12,000	$0	$0	$0	$36,739	**$205,266**	
G.2. Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$4,809	$0	$20,222	$102,192	$415,090	$0	$40,187	**$582,500**	
G.3. Juvenile chub monitoring near the LCR confluence (JCM-East)	$153,012	$2,000	$31,156	$301,244	$0	$0	$106,256	**$593,668**	
G.4. Remote PIT-tag array monitoring in the LCR	$22,557	$0	$5,500	$4,000	$0	$0	$6,988	**$39,046**	
G.5. Monitoring humpback chub aggregation relative abundance and distribution	$4,013	$0	$12,436	$79,366	$142,984	$0	$25,177	**$263,976**	
G.6. Juvenile chub monitoring - Western Grand Canyon (JCM-West) (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.7. Chute Falls translocations (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.8. Sampling of springs in the upper LCR (*FY25 project only; unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.9. Movement in western Grand Canyon from system-wide antenna monitoring	$10,946	$0	$47,000	$0	$0	$0	$12,632	**$70,578**	
Total Project G	**$343,864**	**$10,000**	**$128,314**	**$486,802**	**$558,074**	**$0**	**$227,980**	**$1,755,034**	**$101,063**

Fiscal Year 2026									
Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
G.1. Humpback chub population modeling	$201,395	$8,000	$5,000	$0	$0	$0	$48,453	**$262,849**	
G.2. Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$3,017	$0	$20,222	$105,220	$421,215	$0	$41,668	**$591,342**	
G.3. Juvenile chub monitoring near the LCR confluence (JCM-East)	$157,969	$2,000	$29,656	$314,734	$0	$0	$113,985	**$618,344**	
G.4. Remote PIT-tag array monitoring in the LCR	$24,136	$0	$2,000	$2,000	$0	$0	$6,359	**$34,495**	
G.5. Monitoring humpback chub aggregation relative abundance and distribution	$3,017	$0	$12,436	$64,639	$145,034	$0	$22,452	**$247,577**	
G.6. Juvenile chub monitoring - Western Grand Canyon (JCM-West) (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.7. Chute Falls translocations (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.8. Sampling of springs in the upper LCR (*FY25 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.9. Movement in western Grand Canyon from system-wide antenna monitoring (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project G	**$389,535**	**$10,000**	**$69,314**	**$486,593**	**$566,248**	**$0**	**$232,917**	**$1,754,607**	**$101,247**

Project G Humpback Chub Population Dynamics throughout the Colorado River Ecosystem	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
Fiscal Year 2027									
							23.40%		Est Full Rate = 56%
G.1. Humpback chub population modeling	$215,493	$8,000	$5,000	$0	$0	$0	$53,467	**$281,960**	
G.2. Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$3,228	$0	$20,222	$81,204	$399,455	$0	$36,473	**$540,582**	
G.3. Juvenile chub monitoring near the LCR confluence (JCM-East)	$162,811	$2,000	$30,156	$324,740	$0	$0	$121,612	**$641,319**	
G.4. Remote PIT-tag array monitoring in the LCR	$25,826	$0	$2,000	$2,000	$0	$0	$6,979	**$36,805**	
G.5. Monitoring humpback chub aggregation relative abundance and distribution	$3,228	$0	$12,436	$66,912	$147,083	$0	$23,735	**$253,395**	
G.6. Juvenile chub monitoring - Western Grand Canyon (JCM-West) (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.7. Chute Falls translocations (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.8. Sampling of springs in the upper LCR (*FY25 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
G.9. Movement in western Grand Canyon from system-wide antenna monitoring (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project G	**$410,587**	**$10,000**	**$69,814**	**$474,856**	**$546,538**	**$0**	**$242,266**	**$1,754,061**	**$103,899**

Project H: Salmonid (Trout) Research and Monitoring Project

Investigators

Brian Healy[1], Charles Yackulic[1], Kimberly Dibble[1], Josh Korman[2], Bridget Deemer[1], Tom Sabol[1], David Rogowski[3], Lucas Bair[1], Jeff Arnold[4], Molly A.H. Webb[5], James A. Crossman[6]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Ecometric Research Inc., Vancouver, Canada
[3]Arizona Game and Fish Department
[4]National Park Service, Glen Canyon National Recreation Area
[5]Bozeman Fish Technology Center, U.S. Fish and Wildlife
[6]BC Hydro, Vancouver, Canada

Project Summary

The Long-Term Experimental and Management Plan (LTEMP; U.S. Department of the Interior, 2016) provides the necessary long-term framework for assessing specific operations at Glen Canyon Dam, including experimental flows as well as other types of management actions conceived during and implemented over the next 20-year period. The LTEMP includes a goal for the rainbow trout (*Oncorhynchus mykiss*) fishery in Glen Canyon: *"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"*. For these reasons, the Salmonid Research and Monitoring Project, which includes research and monitoring of trout, was developed having the long view, to inform stakeholders and management responses to unanticipated and emerging risks (e.g., brown trout *Salmo trutta*; Runge and others, 2018). Rapidly changing conditions related to basin-wide water management and upstream reservoir dynamics have led to occurrences of low dissolved oxygen (DO), warming temperatures, and new warm-water nonnative species expansion in Glen Canyon requiring additional quantitative monitoring sensitive to these changes (Dibble and others, 2021; Bruckerhoff and others, 2022; Eppehimer and others, 2024). Water quality and temperature changes influence populations of salmonids in Glen Canyon (Korman and others, 2021; Korman and others, 2023). Given these new developments, it is unclear whether the new expansion of warm-water nonnative species will disrupt the balance between salmonids and endangered native fishes downstream, and the rainbow trout fishery in Glen Canyon.

In general, the study design described in the previous two work plans (FY 2018-20, FY 2021-23 Triennial Work Plans [TWP]) is still relevant for addressing management questions posed in the LTEMP, with similar designs likely relevant to the GCDAMP long into the future.

Importantly, recent changes in the water quality and temperatures discharged from Glen Canyon Dam as reservoir storage in the Colorado River basin declines may potentially impact salmonid populations (Bruckerhoff and others, 2022; Healy and others, 2023). Operational changes designed to respond to warm-water introduced fish expansion and other ecological changes are being proposed by Reclamation (e.g., SEIS, Bureau of Reclamation, 2024). Additionally, GCDAMP stakeholders and tribes have requested the GCMRC consider and reduce overlapping projects to minimize handling of fish out of respect for cultural values and to address fish health concerns, and to enhance monitoring and research efficiencies and optimize information gathering for decision-making. We recognize monitoring and research related to LTEMP salmonid goals needs to be precise and sensitive to anticipated short- and long-term ecosystem changes. Thus, some modifications to this project are proposed for the 2025-2027 TWP. The type of quantitative approach ongoing and proposed herein is appropriate for understanding large and complex ecosystems, particularly, when quantifying drivers of rainbow trout and brown trout population dynamics. This research project proposes to evaluate (1) the effect of ongoing ecological changes (i.e., temperature, DO, warm-water species expansion) on trout somatic growth, reproduction, recruitment, and survival, (2) effects of spring and fall high flow events (HFEs) on trout recruitment, dispersal, and growth, (3) factors controlling trout recruitment and dispersal into Marble Canyon and Little Colorado River (LCR) reaches, (4) factors controlling the quality of the trout fishery (growth, sexual maturity, and angler catch rates), and (5) factors regulating brown trout and other nonnative fish population dynamics, as well as efficacy of an incentivized brown trout harvest program. Summarized below are monitoring and research elements that address the primary study objectives.

Hypotheses and Science Questions

Most of the science questions, as originally proposed in the FY 2021-23 TWP (U.S. Department of the Interior, 2020) and extended in FY 2024, remain relevant now; however, we have revised the list, placing more emphasis on changing environmental conditions and brown trout, because of the relatively unclear risk posed by this species, new expansion of warm-water nonnative species, and recent declines in trout populations in Glen Canyon.

1) What are the effects of changing conditions downstream of Glen Canyon Dam (i.e., DO, water temperature) on trout recruitment, growth, and survival?
2) What are the effects of flow experiments and other management actions (removals or flow management to suppress warm-water nonnative species) on trout population dynamics?
3) What controls rainbow and brown trout dispersal from Glen Canyon downstream into Marble and Grand canyons?

4) What factors control the quality of the rainbow trout fishery, and how does electrofishing capture efficiency influence interpretation of rainbow trout fishery metrics?

5) How do expansions of warm-water nonnative fish species influence trout population dynamics?

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

7) How is climate change likely to impact the rainbow trout fishery below Glen Canyon Dam in short- and longer-term periods?

8) Are certain operations of Glen Canyon Dam more conducive than others to allow long-term coexistence of a high-quality rainbow trout fishery with downstream native fish species?

Background

The LTEMP identified potential flow experiments to improve conditions for fishes, benefit the food base, and improve sediment conditions and rebuild sandbars (U.S. Department of the Interior, 2016). Some experiments originally proposed to limit rainbow trout recruitment in Glen Canyon (trout management flows; TMFs) may not occur during the FY 2025-27 TWP; however, new flow actions are being proposed and analyzed to suppress warm-water nonnative species reproduction that may also influence population dynamics of trout and other species (Bureau of Reclamation, 2024). It is likely that extrinsic factors such as DO and temperature variation 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 and others.

Brown trout are highly piscivorous and may compete with native fish species (Yard and others, 2011; Whiting and others, 2014), leading to restricted native fishes in habitats where brown trout achieve high densities (Healy and others, 2020). The expansion of brown trout in Glen Canyon, which was linked partially to immigration related to fall high flow experiments (HFEs) and a management action to suppress brown trout in Grand Canyon (Healy, and others, 2022), poses a significant threat to the rainbow trout fishery and likely to endangered humpback chub (*Gila cypha*) populations residing downstream in and near the Little Colorado River (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 (Coggins and others, 2011; Healy and others, 2020). Bright Angel Creek trout suppression is ongoing, however dispersal of brown trout from the mainstem may augment the spawning population (Akland, 2023; Healy and others, 2023).

In 2008, large numbers of YOY rainbow trout were produced in Glen Canyon following a spring HFE (Korman and others, 2011), some of which may have subsequently dispersed downstream (Korman and others, 2012). Further research has clarified the role of HFEs, nutrient dynamics, prey availability, and competition in driving rainbow trout population dynamics (Korman and others, 2021; Korman and others, 2023; Yard and others, 2023). In the LTEMP Record of Decision (ROD; U.S. Department of the Interior, 2016), a two-year moratorium was imposed due to the possible relationship between spring HFEs and trout recruitment; however, sediment-triggered spring HFEs are now allowed.

Flow variability can influence trout reproductive success – spring floods can decrease survival following emergence via energetic constraints (Cattanéo and others, 2002; Lobón-Cerviá, 2004; Healy and others, 2023). While fall HFEs have occurred concurrently with the increase in brown trout recruitment, there has been no causal link established between the two phenomena, suggesting additional research is needed.

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 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.

With impending changes in basin-wide water availability and water management decisions, understanding how temperature and flow variability interacts with other extrinsic or intrinsic factors to influence trout population dynamics. 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 FY 2025-27 TWP. The project elements proposed herein are driven by six overarching research questions that apply to both rainbow and brown trout.

What are the Effects of Changing Conditions Downstream of Glen Canyon Dam (i.e., Dissolved Oxygen, Water Temperature) on Trout Recruitment, Growth, and Survival?

Significant changes in water quality and temperature have occurred over the course of the last work plan (Figure 1; U.S. Geological Survey, 2024) that will likely effect population dynamics for trout and other fishes in Glen Canyon and downstream (Korman and others, 2023). Dissolved oxygen (DO) and temperature can have interacting effects on fish metabolic rates that affect survival, growth, and energy allocated to reproduction (Hanks and Secor, 2010; Waldrop and others, 2020).

Current models of DO in GCD releases model bypass DO based on observations during HFEs (Hueftle and Stevens, 2001; Vernieu, 2010). For example, bypass releases of 15,000 cfs during the 2008 high flow experiment resulted in supersaturated DO concentrations (12.6 mg/L; Vernieu, 2010) below the dam.

The degree of supersaturation under lower bypass releases (such as with cold shock proposed in supplemental EIS; Bureau of Reclamation, 2024) is a significant uncertainty and would help inform modeling such as that used to inform the NEPA/EIS compliance processes (Yackulic and others, 2024).

Constraints on prey production related to reservoir nutrient dynamics may also influence abundance of rainbow trout in Glen Canyon (Yard and others, 2023). Recent preliminary data collected in 2023 through project H suggests declines in trout body condition, growth rates (Figure 2), and catch rates; additional analysis is needed to understand the drivers of these trends, including interactions between reduced DO, higher water temperatures, and potential food limitations. Continued mark-recapture sampling, along with analysis of reproductive status data (see Crossman and others, 2022), is planned in the FY 2025-27 work plan for project H to further investigate questions related to the effects of changing environmental conditions on trout population dynamics. We will study associations between season-specific estimates of abundance, body condition, growth and survival rates, and spatial and temporal trends in DO, temperature and food (see project F), to understand the strength of drivers of rainbow trout population dynamics. Understanding how these variables interact to influence trout population dynamics and the health of the rainbow trout fishery will help inform decision-making for potential management actions. During the next work plan, management actions designed to influence dissolved oxygen (injection at the penstocks), temperature (use of bypass tubes to release cold water), or stocking may be considered by management agencies. Basin-wide water management decisions, which influence reservoir levels, temperature, and fish distribution or persistence of salmonids (Dibble and others, 2021; Bruckerhoff and others, 2022; Healy and others, 2023), would also be informed by the results of Project H.

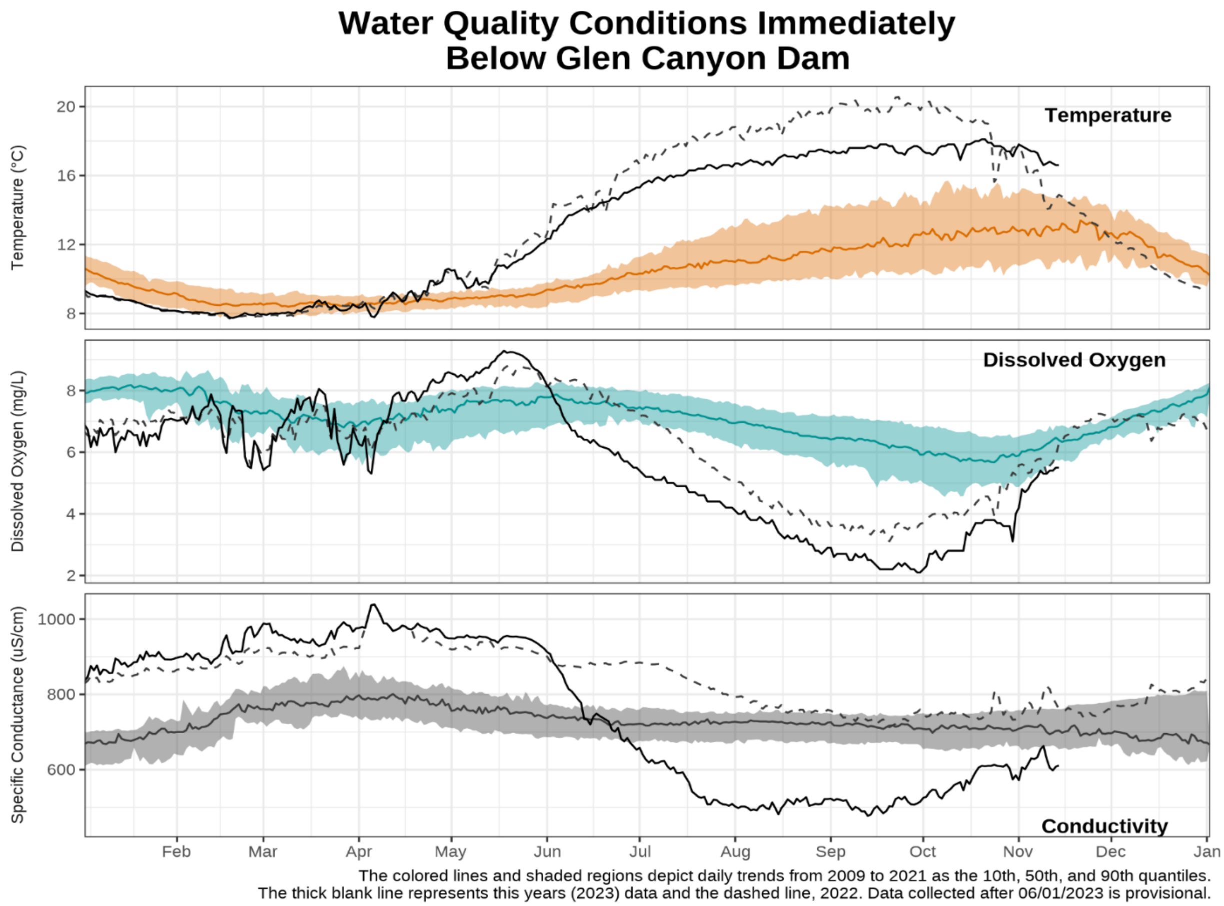

Figure 1. Water quality in Glen Canyon in 2022 and 2023 compared to long-term trends from 2009-2021 (U.S. Geological Survey, 2024).

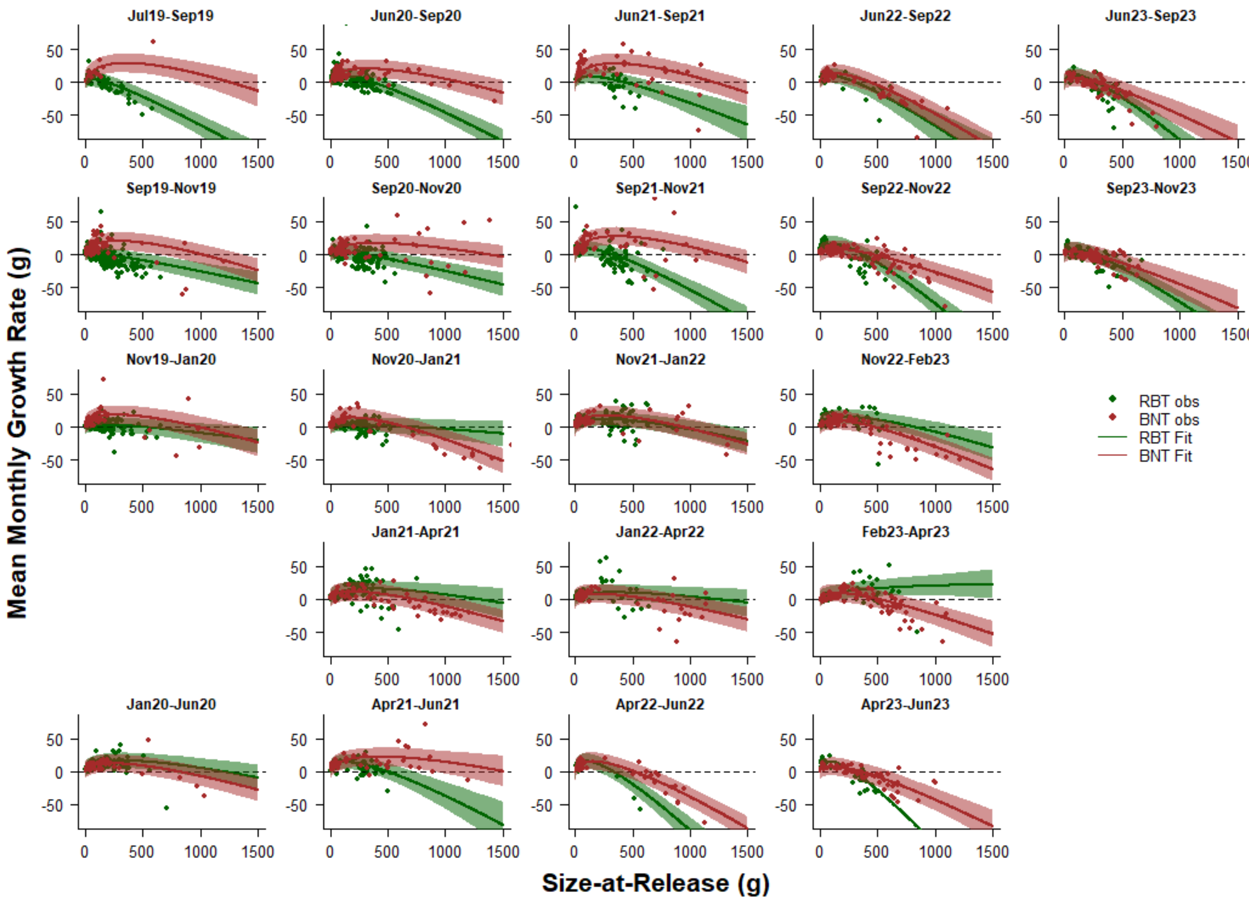

Figure 2. Growth rates in rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) in Glen Canyon, based on mark-recapture data collected 2019-2023 (Korman and others, 2024).

What are the Effects of Spring and Fall HFEs, Macroinvertebrate Production Flows, and other Management Actions (Flow Management to Suppress Warm-Water Nonnative Species) on Trout Population Dynamics?

LTEMP flow experiments and non-flow fisheries management actions are occurring or planned to occur in Glen Canyon to improve LTEMP resource conditions (U.S. Department of the Interior, 2016), which may influence rainbow trout population dynamics. HFEs in spring or fall, or temperature management strategies using Glen Canyon Dam bypass tubes to limit smallmouth bass (*Micropterus dolomieu*) reproduction, and potentially minimize entrainment through Glen Canyon Dam (U.S. Bureau of Reclamation, 2024; also see Project I), among other strategies, may be implemented during the FY 2025-27 work plan. An increase in rainbow trout growth rates and recruitment in Glen Canyon was observed following the 2008 spring HFE (Korman and others, 2011), but long-term mark-recapture monitoring and analysis of TRD data since 2008 have provided new insights into the role of dam discharge, competition, prey availability, and nutrient dynamics in driving Glen Canyon trout population dynamics, (Korman and others, 2021, 2023). Thus, it is uncertain whether future spring HFEs will produce a similar response because 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). Temperature may have an overriding influence on trout growth and survival, but the population-level response in rainbow and brown trout may depend on the temperature management strategy implemented. Therefore, if HFEs or other flow and temperature management actions are implemented, ecosystem responses will be evaluated using the proposed Trout Recruitment and Growth Dynamics (TRGD) sampling program, as described below

There have been several 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. Conversely, high flows during the emergence of brown trout fry may also limit recruitment (Healy and others, 2023). Food availability (e.g., rainbow trout fry) or redd superimposition by rainbow trout, temperature (Healy and others, 2023), or immigration from downstream reaches (Healy and others, 2022) could also influence brown trout population dynamics. Therefore, additional monitoring and modeling of trout growth and other extrinsic factors may resolve uncertainties about the effects between species and on brown trout population dynamics. 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). Data analysis is proposed to reassess the hypotheses in Runge and others (2018), and potentially others (e.g., larger rainbow trout competing with smaller brown trout; Blanchet and others, 2007), and examine how adult growth following a fall HFE influences sexual maturation, fecundity, and, by extension, recruitment the following year (Project Element H.3).

What Controls Rainbow and Brown Trout Dispersal from Glen Canyon Downstream into Marble And Grand Canyons?

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 the Interior, 2016). 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. 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).

Recent declines in recruitment of trout in Glen Canyon (red bars, Figure 3) and apparent declines in overall catch in 2024 suggest downstream dispersal rates and our assumptions of drivers of dispersal may change.

However, metapopulation modeling (Healy and others, 2023), passive integrated transponder (PIT) tag detections (Schelly and others, 2021), and evidence from brown trout otolith microchemistry (Akland, 2023) suggests the potential for movement of brown trout from mainstem reaches into tributaries that may be important for native fishes and therefore negatively impact native fish populations (Healy and others, 2020).

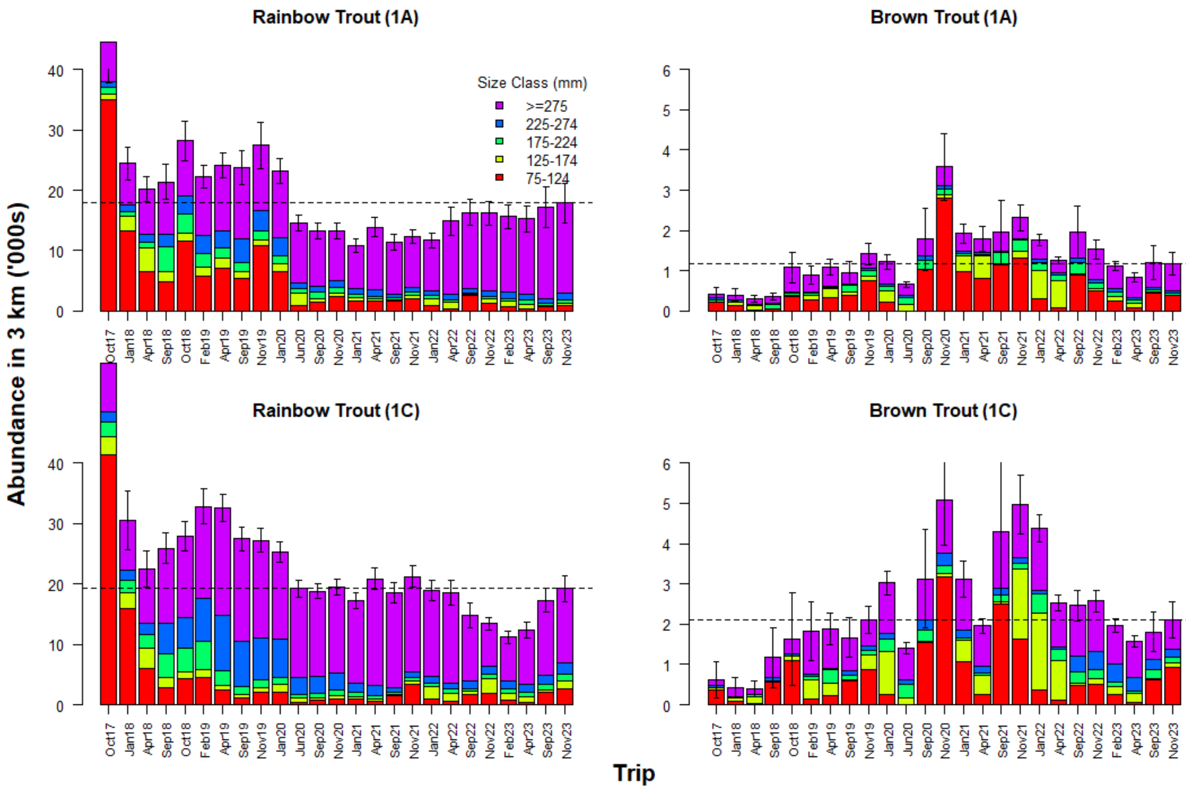

Figure 3. Trends in rainbow trout (*Oncorhynchus mykiss*; left column) and brown trout (*Salmo trutta*; right column) in TRGD sites 1A and 1C (U.S. Geological Survey, 2024).

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. Dispersal between reaches of river or tributaries with suitable spawning habitat may serve to maintain a metapopulation of brown trout that is resilient to suppression efforts by the National Park Service (described in Healy and others, 2020). While brown and rainbow trout numbers have been low in Grand Canyon in recent years (Fonkin and others, 2023), depending on the selected dam discharge strategy to suppress spawning of warm-water nonnative fishes such as smallmouth bass, rapid rebounds in salmonids may occur. 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).

We will also integrate data collected for trout in tributaries and the Colorado River to understand movements of trout, including to culturally sensitive areas that are also important for native fishes (LCR inflow).

What Factors Control the Quality of the Rainbow Trout Fishery, and how does Electrofishing Capture Efficiency Influence Interpretation of Rainbow Trout Fishery Metrics?

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. Understanding factors influencing the quality of the rainbow trout fishery is an important endeavor given the economic importance of the fishery to Northern Arizona (Bair and others, 2016). Anecdotal reports from anglers in January-April 2024 suggest the fishery is in steep decline, highlighting the importance of understanding causes of the decline if management responses are to be developed.

There is seasonal variability in rainbow trout condition factor for large sized fish (> 300 mm FL) (Korman and others, 2017). Water quality, reduced condition, and competition for prey likely led to decreased survival of larger sized fish and ultimately reduced rainbow trout abundance in the Lees Ferry trout fishery in recent years (Korman and others, 2021; Korman and others, 2023; Yard and others, 2023). Notably, relative condition factor for brown trout has been 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 – nonetheless, condition of both species has declined recently (Figure 4). 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).

Capture probability biases due to variation in size structure or environmental conditions at the time of sampling (Korman and Yard, 2017; Healy and others, 2022) can strongly bias interpretation of trends in metrics (catch-per-unit-effort; CPUE) used to assess the quality of the fishery (Glover and others, 2019). For example, index based metrics such as CPUE rely upon the assumption that the index is consistently proportional to actual abundance of trout present in the system (Williams and others, 2002) – this assumption is unlikely to be true based on capture probability estimates for both brown and rainbow trout showing large fish are less likely to be captured than small individuals (Korman and Yard, 2017; Yackulic and others, 2020; Healy and others, 2023). In this work plan, we propose to focus more on mark-recapture based monitoring to track trends in the rainbow trout fishery. This will require a crosswalk between past CPUE-based monitoring and mark-recapture data. Depending on the needs and desires of managers, we could recalibrate metrics used to track trends in fishery quality by accounting for biases that could arise in abundance estimation due to individual (size) and temporal heterogeneity in capture probability.

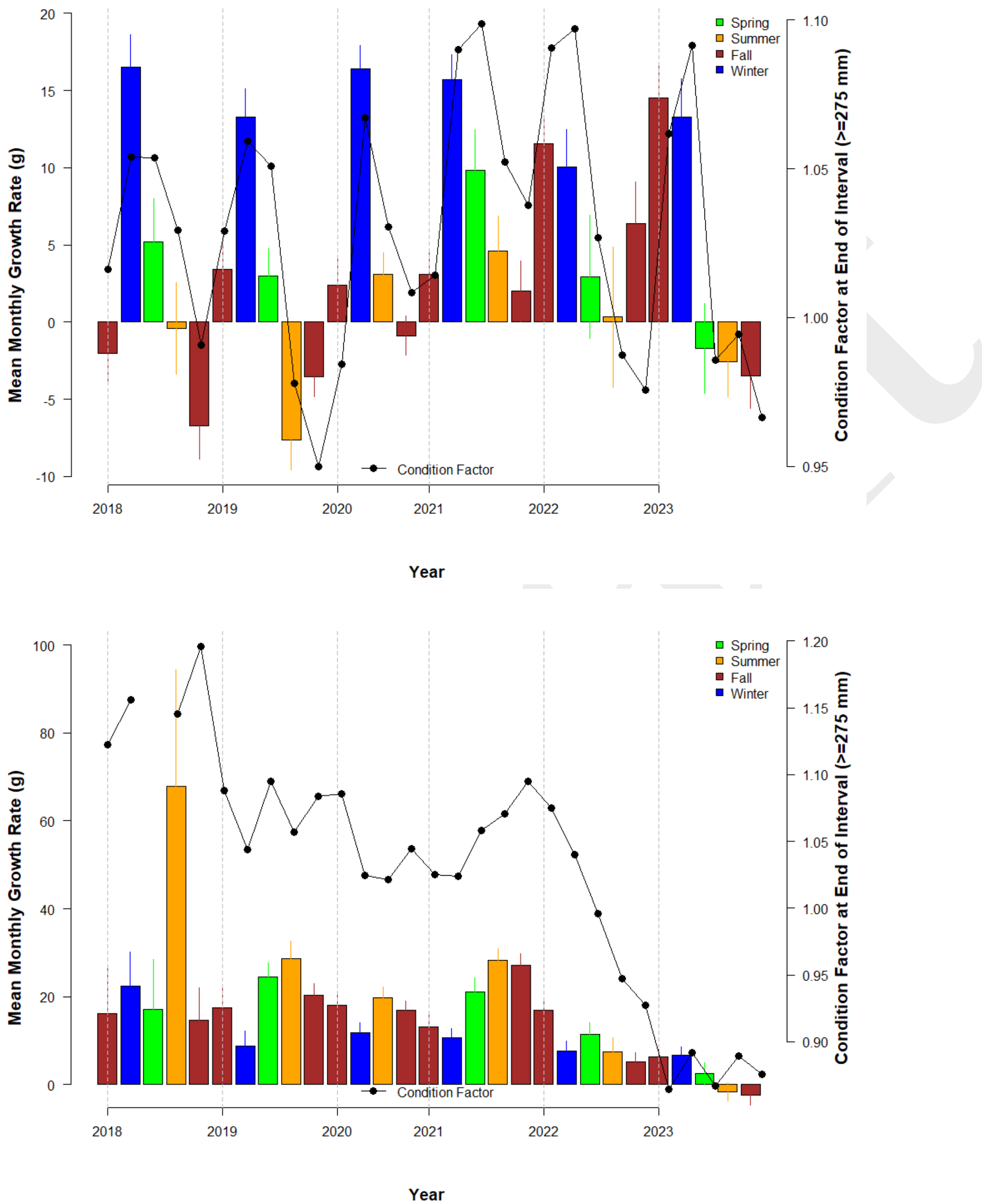

Figure 4. Condition and growth rates of rainbow trout (*Oncorhynchus mykiss*; top) and brown trout (*Salmo trutta*; bottom) in the Glen Canyon reach of the Colorado River, Arizona, USA, from mark-recapture data collected under project H (U.S. Geological Survey, 2024).

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).

How do Expansions of Warm-Water Nonnative Fish Species Influence Trout Population Dynamics?

Several warm-water nonnative fishes have increased in number or have been newly detected downstream of Glen Canyon Dam, including green sunfish (*Lepomis cyanellus*), smallmouth bass, and walleye (*Sander vitreus*). These warm-water species are known to prey upon or potentially compete with native fishes of the Colorado River basin (Rogosch and Olden, 2020) and salmonids elsewhere (Carey and others, 2011), resulting in constrained distribution or abundance of native fishes (Hughes and Herlihy, 2012; Walsworth and Budy, 2015). Outcomes of biotic interactions with salmonids in a food-limited system such as Glen Canyon (Korman and others, 2021) are difficult to predict. We will investigate relationships between abundance or relative abundance (CPUE) of warm-water native fishes and other environmental factors with demographic and somatic growth rates of trout. However, we recognize separating the effects of potential competitors or predators and changing environmental conditions (e.g., temperature) may be difficult. Understanding the relative strength of these potential drivers of trout population dynamics may be nonetheless important to decision-making related to dam operations or nonnative fish suppression efforts, if a goal to maintain a healthy rainbow trout fishery remains a priority for managers.

What Factors Regulate Brown Trout Population Dynamics in Glen Canyon, and what is the Management Efficacy of Control Actions?

As mentioned above, it is unclear what factors led to the increase of brown trout abundance in Lees Ferry (Runge and others, 2018). 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. In addition, Healy and others, (2023) used a metapopulation viability model to further simulate the effects of management actions meant to suppress brown trout abundance while accounting for the effects of declining reservoir levels and warming temperatures. 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 (GLCA) is implementing an incentivized harvest of larger-sized brown trout.

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.3).

Ongoing Monitoring Studies (modified)

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

The objective of this project element is to monitor the basic fish population characteristics, including relative abundance, size composition, distribution, and recruitment of rainbow trout and brown trout. In past work plans, the monitoring program used catch-per-unit effort (CPUE) metrics designed to be able to detect population level changes over a five-year or greater time scale; however, for the FY 2025-27 work plan we propose to combine staffing resources and electrofishing-based monitoring trips between H.1 and H.2 to enable more precise and sensitive mark-recapture monitoring, while also adding days onto 2 monitoring trips (June and October) for nonnative fish species surveillance (an additional downstream electrofishing monitoring trip is proposed in lieu of Lees Ferry CPUE trips as well; see Project I). In total (including H.1 and H.2), trout monitoring trips will be reduced from 8 to 4, compared to the previous work plan. Despite these changes, CPUE will continue to be calculated from data collected during the remaining 4 mark-recapture-focused trips.

The Lees Ferry Creel Survey and Arizona Game and Fish Department (AGFD) Citizen Science Project (FY 2021-23 and previous TWPs), which directly evaluates the quality and changes in the recreational experience of angling in the rainbow trout fishery in the Lees Ferry, Glen Canyon National Recreation Area is proposed to continue. AGFD will continue conducting a citizen science project that utilizes fishing guides to collect length data on fishes caught by their clients to reduce bias in angler catch quality (i.e., number of fish ≥ 14" and fish ≥ 20").

Continuing Research Studies (modified)

Project Element H.2. Trout Reproductive and Growth Dynamics

This is a research project referred to as the Trout Reproductive and Growth Dynamics (TRGD) project, which is designed to determine the effects of LTEMP ROD flows on the recruitment of young-of-year (YOY) rainbow and brown trout in Glen Canyon, 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, temperature, DO, etc.) that control abundance and growth of the Glen Canyon trout population(s) to better predict the effects of management actions and environmental changes. This improved understanding could inform decisions related to future management of the trout fishery, or 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 and controlling recently established brown trout numbers (Runge and others, 2018). For purposes of study replication, a *multi-reach mark-recapture sampling design* was established having two sub-reaches, each with an assigned 3-km length (sum 24% areal coverage). Trout (and potentially other species) will continue to be marked with a passive-integrated transponder (PIT) tag, and recapture data will be analyzed to estimate demographic parameters using appropriate mark-recapture models (Kendall, Pollock, and Brownie, 1995; Korman and others, 2021). We will also continue to monitor DO levels in the Lees Ferry reach to understand how temporal and spatial variation relates to trout growth, body condition, and demographic rates.

This spatial coverage has allowed for the replication necessary for assessing experimental flow effects (Korman and others, 2021, 2023), and allows the TRGD program to maintain the necessary long-term analysis (comparisons and contrasts) associated with the Natal Origin project (2012-2017; FY 2015-17 TWP, Project Elements 9.1, 9.2, and FY 2018-20 TWP). Data from the TRGD project are used to inform development of a spatially stratified open population model for rainbow trout (Korman and Yard, 2017; Korman and others, 2017), and a population model for brown trout (Runge and others, 2018; Yackulic and others, 2020). These models provide estimates of how experimental flows and riverine conditions influence survival and recruitment of early YOY, as well as other size-classes of trout that may exhibit compensatory response in the population. Trout dispersal out of Glen Canyon will continue to be monitored in Marble Canyon, as well as trout population dynamics and near the LCR confluence in conjunction with humpback chub monitoring (Project G). Lastly, monitoring population dynamics of brown trout provides the means to assess incentivized take harvest measures by National Park Service (Project Element H.3). For the FY 2025-27 work plan, we propose to minimize project costs and avoid monitoring during periods of elevated stress to trout when low DO or high temperatures have been observed to occur (fall), by reducing the total number of electrofishing monitoring trips in Project Elements H.1 and H.2 from 8 to 4 trips (also see Project Element H.1 description above).

Project Element H.3. Salmonid Modeling

Salmonid modeling priorities in this work plan include 1) estimating the efficacy of incentivized harvest on brown trout (by updating brown trout population model and incorporating harvest data) to inform managers and project J, 2) reassessing the brown trout hypotheses explored in Runge and others (2018) using data collected in recent years and based on natal origins and movement studies (Healy and others, 2022; Akland, 2023), 3) continuing to develop models to predict recruitment and outmigration of rainbow and brown trout - outmigration of trout and other nonnative fishes from Lees Ferry to downstream areas, including tributaries, can enhance resilience of nonnative salmonid populations (Healy and others, 2023) and is seen as detrimental to native fish conservation goals (Yackulic and others, 2018; Healy and others, 2020), 4) estimating population dynamics of rainbow and brown trout in the Lees Ferry reach in response to experimental flows and environmental conditions, and 5) develop a workflow and analytical approach for calculating LTEMP metric scores for salmonids related to rainbow trout and nonnative fish goals. Finally, we plan to finish the development of manuscripts using reproductive status data collected in the previous work plan, which revealed that condition-effected sexual maturation rate appears to play an important role in regulating annual recruitment. Understanding this relationship may help us develop a more reliable method for forecasting and responding to large recruitment events.

Outcomes and Products

Project Element H.1.

Outcomes

- 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

- Presentation(s) and/or annual report (presentations will be given at the Annual Reporting meeting and at regional meetings).

Project Element H.2.

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.
- Evaluate how experimental flows and management actions 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

- 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 and changing environmental conditions, including the introduction and expansion of warm-water nonnative fish populations.

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 and brown trout recruitment and outmigration.

Personnel and Collaborations

The overall project lead for Project H is Dr. Brian Healy, a Supervisory Research Fish Biologist at GCMRC who specializes in population dynamics, quantitative ecology, and decision science. 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. Kimberly Dibble, a Supervisory Research Fish Biologist at GCMRC with expertise in fish physiology, otolith microstructural analysis, and metadata analysis. Dr. Josh Korman is a Fish Biologist with Ecometric Research, Inc. specializing in analytical models and database development, population dynamics, and modeling capabilities. Dr. Bridget Deemer is a Research Ecologist at GCMRC specializing in water quality and limnology. 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. 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 Project Element H.3.

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Budget

Fiscal Year 2025									
Project H Salmonid Research and Monitoring	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							21.80%		Est Full Rate = 55%
H.1. Rainbow trout fishery monitoring in Glen Canyon	$7,609	$0	$0	$0	$88,000	$0	$4,299	**$99,908**	
H.2. Experimental flow assessment of trout recruitment (TRGD)	$80,450	$2,500	$88,800	$112,771	$0	$0	$62,026	**$346,547**	
H.3. Salmonid modeling	$38,163	$0	$6,000	$0	$0	$0	$9,628	**$53,791**	
Total Project H	**$126,222**	**$2,500**	**$94,800**	**$112,771**	**$88,000**	**$0**	**$75,952**	**$500,245**	**$35,075**

Fiscal Year 2026									
Project H Salmonid Research and Monitoring	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
H.1. Rainbow trout fishery monitoring in Glen Canyon	$7,402	$0	$0	$0	$88,000	$0	$4,313	**$99,714**	
H.2. Experimental flow assessment of trout recruitment (TRGD)	$81,826	$2,500	$68,800	$115,875	$0	$0	$60,794	**$329,795**	
H.3. Salmonid modeling	$71,181	$0	$6,000	$0	$0	$0	$17,443	**$94,624**	
Total Project H	**$160,408**	**$2,500**	**$74,800**	**$115,875**	**$88,000**	**$0**	**$82,550**	**$524,133**	**$37,469**

Fiscal Year 2027									
Project H Salmonid Research and Monitoring	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
H.1. Rainbow trout fishery monitoring in Glen Canyon	$7,920	$0	$0	$0	$88,000	$0	$4,493	**$100,413**	
H.2. Experimental flow assessment of trout recruitment (TRGD)	$87,553	$2,500	$68,800	$118,998	$0	$0	$65,017	**$342,869**	
H.3. Salmonid modeling	$76,163	$0	$6,000	$0	$0	$0	$19,226	**$101,390**	
Total Project H	**$171,637**	**$2,500**	**$74,800**	**$118,998**	**$88,000**	**$0**	**$88,737**	**$544,671**	**$39,604**

Project I: Nonnative Aquatic Species Monitoring and Research

Investigators

Kimberly Dibble[1], Charles Yackulic[1], Drew Eppehimer[1], David Rogowski[2], Megan Osborne[3], Thomas Turner[3], Thomas Franklin[4], Maria Dzul[1], Brian Healy[1], David Ward[5], Bridget Deemer[1], Ian Bishop[1], Ted Kennedy[1], Justin Sanders[6], Terra Kelly[7], Eric Frye[1], Kate Behn[1], Lindsay Hansen[1], Ben Miller[1], John Fennell[2], Dale Fonken[2], Trenton Schipper[2]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Arizona Game and Fish Department
[3]University of New Mexico, The Museum of Southwestern Biology
[4]U.S. Forest Service
[5]U.S. Fish and Wildlife Service
[6]Oregon State University
[7]EpiEcos

Project Summary and Purpose

Maintaining self-sustaining native fish populations within the Colorado River and minimizing the presence and expansion of aquatic nonnative species are two resource goals outlined in the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) and associated Biological Opinion for the operation of Glen Canyon Dam (U.S. Department of the Interior, 2016a, b; U.S. Fish and Wildlife Service, 2016). These two resource goals are closely linked together in that nonnative warm-water fishes are largely incompatible with Colorado River native fishes (Marsh and Pacey, 2005; Minckley and Marsh, 2009). Nonnative warm-water sport fishes prey upon juvenile native fishes, and once established, can cause rapid disappearance of native fishes (Moyle and others, 1986).

In both the upper and lower Colorado River Basins, warm-water predatory fishes are implicated in the lack of recruitment and subsequent population declines of native fishes (Mueller, 2005; Martinez and others, 2014). Outside of preventative measures, control methods are typically most cost effective and successful when nonnative species are detected early (Leung and others, 2002; Dawson and Kolar, 2003). As such, a robust monitoring and research program increases the likelihood that new introductions and expansions of nonnative fish species will be detected early and that managers will have the information needed to control pest species before its distribution expands and abundance increases.

Rapidly changing conditions in the Colorado River downstream from Glen Canyon Dam since 2022, and the immediate threat of smallmouth bass (*Micropterus dolomieu*) and other predatory nonnative species to the Colorado River ecosystem, have necessitated a shift in focus for Project I relative to previous work plans.

The focus of Project I will primarily be on nonnative fish/aquatic species, since the category for 'native fishes' was moved to Project N [except for Project Element I.1, which focuses on both native and nonnative fishes]. In the Glen Canyon Dam Adaptive Management Program FY 2025-27 Triennial Budget and Work Plan (hereafter, FY 2025-27 TWP), we will focus our research and monitoring efforts on detecting new nonnative species or distributional shifts in nonnative species, use genomic tools to determine nest origin and potentially the abundance of nonnative fishes being removed from the river, conduct enhanced biosurveillance through additional trips and environmental DNA (eDNA) monitoring, assess entrainment potential for nonnative fish in Lake Powell, and analyze data from federal and state partners to assess the efficacy of management actions to control nonnative populations of smallmouth bass.

In total, the number of elements in Project I will increase by one in the FY 2025-27 TWP relative to the FY 2021-23 TWP. We propose to continue long-term, standardized monitoring conducted by the Arizona Game and Fish Department (AGFD) throughout the Colorado River from Lees Ferry (RM 0) to Pearce Ferry (RM 281) for the combined purposes of tracking the status of native and nonnative fishes, as well as identifying new nonnative aquatic species (Project Element I.1). These data can be used to determine the distribution of nonnative fishes throughout Glen and Grand Canyons and quantify growth rates through use of length-frequency histograms and modal progression analysis.

We propose to pursue kinship genetic analysis to evaluate the relatedness of individual smallmouth bass and determine whether there is suggestive evidence of local recruitment (i.e., most individuals captured near the slough are siblings or half-siblings) or entrainment (i.e., most individuals captured near the dam represent a greater number of parent-offspring pairs; Project Element I.2). These data can also be used to conduct close-kin mark-recapture analysis to estimate abundance and other demographic parameters (e.g., survival, population trends) using kinship relationships of individuals identified by genetic sampling.

We would like to re-focus an existing Project Element (I.3) to detect emerging threats in the Colorado River Ecosystem (CRe), which may include nonnative fishes, parasites, disease, crayfish, gastropods, mollusks, and other nonnative aquatic species. One of the primary methods proposed to detect such threats in this work plan will be the use of eDNA, which is a method that will reduce handling of fish through the collection of water samples and fish fecal matter.

Last, we propose to add a new Project Element (I.4) that focuses on modeling nonnative fish data from U.S. Geological Survey (USGS), National Park Service (NPS), AGFD, U.S. Fish and Wildlife Service (USFWS), and other cooperators. This modeling will support refinement of existing smallmouth bass models, help determine the effectiveness of LTEMP SEIS Flow Experiments and smallmouth bass removal actions and provide science to support discussions of offramps laid out in the Invasive Fish Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023). We also propose to develop a workflow process for an occupancy model in collaboration with Projects H, G, and N that models native and nonnative fish detection data throughout the CRe for the purpose of reporting out to the Glen Canyon Dam Adaptive Management Program

(GCDAMP) on LTEMP Performance Metrics. If flows to disadvantage smallmouth bass are implemented per the preferred alternative in the LTEMP SEIS, we propose to analyze monitoring data to evaluate the effectiveness of smallmouth bass flows, collect larval fishes to determine hatch dates, and collect targeted eDNA samples for smallmouth bass prior to and after the flow. We propose to fund SEIS-related smallmouth bass projects using the Experimental Fund (see Project Elements I.5 and I.6).

Other efforts outside of Project I to increase detections of nonnative fishes include the addition of a boat to the fall USFWS humpback chub (*Gila cypha*) Aggregations Monitoring trip in FY 2025 to seine backwaters for nonnative fishes and collect eDNA samples (Project Elements G.5 and I.3), Juvenile Chub Monitoring in Eastern and Western Grand Canyons (Project Elements G.3 and G.6), USFWS humpback chub Aggregations Monitoring (Project Element G.5), and testing the use of submersible antennas with citizen scientists to detect PIT-tagged fish in less visited areas (new Project Element G.9). Increasing our understanding of smallmouth bass diet is also proposed to continue during this work plan (see Project Element F.4), and we plan on including nonnative fishes in a study to determine standard and active metabolic rates of fish to inform development of ecosystem models proposed in Project Element E.4. Other fishery monitoring efforts conducted by the NPS and other partners augment work funded through GCDAMP to detect nonnative fishes in Glen and Grand canyons. These combined efforts provide important additional detection information of nonnative species throughout the CRe.

Hypotheses and Science Questions

- I.1.1: What is the species composition, relative abundance, longitudinal distribution, and population trends of the native and nonnative fish community inhabiting the CRe?
- I.1.2: Can portable submersible PIT tag antennas be used to detect movement of humpback chub in Grand Canyon?
- I.2.1: What proportion of smallmouth bass captured downstream from Glen Canyon Dam are locally produced or entrained from Lake Powell?
- I.2.2: Is there spatial structure in kinship and are there hotspots with higher densities of related individuals?
- I.2.3: How many parents produced the juveniles, and does genetic data indicate monogamous or polygamous mating in smallmouth bass?
- I.2.4: How comparable are population abundance estimates using close-kin mark-recapture and traditional mark-recapture using green sunfish as a surrogate? Can we use close-kin analysis to obtain accurate estimates of abundance for species that must be sacrificed/removed from CRe?

- I.3.1: What high-risk species in Lake Powell are moving into the Colorado River undetected by traditional sampling techniques?
- I.3.2: How comparable are eDNA methods to traditional sampling gear for detecting sources and dispersal of nonnative fishes in the Colorado River? In comparison to currently used methods, how effective and feasible is using eDNA techniques to monitor changes in distribution and relative abundance of the fish assemblage in relation to dam operations and environmental conditions in the CRe?
- I.3.3: How do the biophysical characteristics of Lake Powell affect the likelihood of nonnative fish entrainment through Glen Canyon Dam?
- I.3.4: What is the incidence of parasite infestation in humpback chub in the Little Colorado River and mainstem Colorado River? Can a molecular assay be developed to reduce handling time and expand the scope of monitoring?
- I.4.1: How does turbidity and temperature affect feeding efficiency and survival of early life stages of smallmouth bass? How does adding turbidity as a parameter in the smallmouth bass population growth model affect performance?
- I.4.2: How effective are management actions (LTEMP Flow Experiments, removals) at reducing smallmouth bass population growth, survival, dispersal, and reproduction?
- I.4.3: What are the long-term drivers of distributional changes in native and nonnative fishes in the CRe?

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 fishes and introduced warm-water fishes such as channel catfish (Hayden, 1992; Minckley and Marsh, 2009). These warm-water fishes 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 in the Lees Ferry reach dropped to 7-10°C by 1973 with little annual variation (Vernieu and others, 2005). 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 several decades. Until 2022, constant cold water largely kept warm-water nonnative fishes 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.

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 (Van Haverbeke and others, 2017), compared to dramatic declines that have occurred in most other portions of the Colorado River Basin during the same period. The river flowing through Grand Canyon warmed enough over the past two decades to support growth of native fishes downstream but was cold enough in the tailwater to support a rainbow trout fishery. Lake Powell elevations were high enough during most of this period that penstocks did not draw from the warmer epilimnion, so entrainment of warm-water nonnative fishes was likely low. Essentially, the river was ‘not too hot, not too cold…but just right’ from a perspective of allowing some level of support for the tailwater trout fishery and native fishes downstream. Further, as Lake Mead dropped in elevation below 346 meters above sea level due to declining basin-wide water supply, Pearce Ferry Rapid emerged near the inflow as the river cut through the reservoir delta outside the original channel. Colorado River water now flows over a bedrock ledge at Pearce Ferry Rapid, and this has been hypothesized to be a barrier to upstream movement of nonnative fishes that prey on native fishes (Kegerries and others, 2020).

Nonnative fishes typically have detrimental impacts on the stability of native fish communities (Erős and others, 2020), and these effects can be exacerbated by drought conditions (Rogosch and others, 2019). Identifying sources of warm-water nonnative 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 nonnative fish is far more environmentally and fiscally desirable than undertaking control or eradication efforts after they become established (Cucherousset and Olden, 2011; Martinez and others, 2014). Introduced fish often grow rapidly with high reproductive potential, and once established, eradication is often essentially impossible and control typically requires long-term and expensive efforts (Pimentel and others, 2000; Simberloff, 2003; Mueller, 2005; Johnson and others, 2009; McIntosh and others, 2010; Martinez and others, 2014).

In 2022, warm-water nonnative fishes including smallmouth bass (*Micropterus dolomieu*), green sunfish (*Lepomis cyanellus*), and walleye (*Sander vitreus*) were captured in unprecedented numbers in the Colorado River downstream from Glen Canyon Dam during routine fish monitoring efforts by state and federal agencies. Reservoir levels in Lake Powell had precipitously declined during a multi-decadal drought, resulting in reservoir releases from the warmer epilimnion (top layer) and upper metalimnion (middle layer) of the lake.

Biological activity and fish production is highest in the warmer epilimnion of Lake Powell, so as reservoir levels dropped more fish were entrained and moved through the penstocks into the downstream river. Warmer reservoir releases likely supported higher survival and successful reproduction of warm-water entrained fishes including smallmouth bass (Dibble and others, 2021; Bruckerhoff and others, 2022; Eppehimer and others, 2024). Smallmouth bass are a species of high concern to resource managers because they are highly piscivorous and have led to population-level declines in native species in regions where they have been introduced (Loppnow and others, 2013).

Recognizing the threat of smallmouth bass and other warm-water nonnatives to threatened and endangered fish recovery, federal and state agencies mobilized around efforts to characterize the threat, remove warm-water nonnatives from the Colorado River in Glen and Grand Canyons, and develop models to support identification of flow management strategies to disadvantage warm-water nonnative fish. The Smallmouth Bass Ad Hoc Group (SBAHG), through the Technical Work Group of the GCDAMP in partnership with GCMRC and Reclamation, developed an Invasive Fish Species Strategic Plan (hereafter, 'strategic plan') (Smallmouth Bass Ad Hoc Group, 2023) with a goal to prevent, detect, and respond to the establishment of nonnative fish in the Colorado River ecosystem. This plan outlines a strategy to prevent fish passage through Glen Canyon Dam while also preventing establishment downstream from the dam.

Management actions taken by federal and state partners from 2022-2024 in accordance with the strategic plan included smallmouth bass and other nonnative fish removals and monitoring in Glen Canyon National Recreation Area (GLCA) and Grand Canyon National Park (GRCA) (Smallmouth Bass Ad Hoc Group, 2023). In addition, GCMRC scientists provided modeling support for the development of a supplemental Environmental Impact Statement (SEIS) to the LTEMP EIS, which evaluated management alternatives to reduce the likelihood of smallmouth bass reproduction and population growth by reducing water temperature (via river outlet release) and/or by spiking flows within powerplant capacity.

As indicated in the 2016 Biological Opinion for the LTEMP EIS, the Bureau of Reclamation (hereafter, 'Reclamation') will conduct planning and compliance for implementation of rapid response control efforts for newly establishing or existing deleterious nonnative species within and contiguous to the action area (U.S. Fish and Wildlife Service, 2016). Before any management actions can occur, monitoring must first detect the introduced fish and research must be conducted to evaluate risks and inform managers whether control efforts are warranted and feasible. This project provides the information that will allow for effective integration of monitoring, research, and nonnative species management in the Colorado River downstream from Glen Canyon Dam.

Proposed Work

Project Element I.1. System-wide Native Fishes and Nonnative Aquatic Species Monitoring

David Rogowski[1], John Fennell[1], Dale Fonken[1], Trenton Schipper[1]

[1]Arizona Game and Fish Department

The objective of this project element is to provide long-term data on the longitudinal distribution and status of the fish assemblage in the mainstem Colorado River from Lees Ferry (RM 0) to Pierce Ferry Rapid (RM 281). These data could be used with other data sources in the development of LTEMP Performance Metrics 10.1-10.8, which are focused on detecting the presence and reproduction of aquatic nonnative species downstream from Glen Canyon Dam. Annual AGFD data on adult flannelmouth sucker CPUE for three years following LTEMP Experimental Actions is being used as a surrogate for effects on razorback sucker per the 2016 Biological Opinion (U.S. Department of the Interior, 2016a).

In the FY 2021-23 work plan, AGFD conducted one spring sampling trip in FY 2021 and FY 2022 and two spring sampling trips in FY 2023, combined with an annual fall trip that sampled the last 15 miles of river upstream from Pearce Ferry Rapid. In this FY 2025-27 proposal, AGFD will conduct one spring sampling trip annually from Lees Ferry to Pearce Ferry and add a new system-wide sampling trip in fall that is timed when nonnative detections are likely to be highest during the warmest reservoir release months of the year. This trip could replace or be coordinated with the existing fall trip that samples the last 15 miles of river, since that area would be covered by the proposed new fall system-wide sampling trip. Additional nonnative fish surveillance that was conducted in the Lees Ferry reach during previous AGFD trout monitoring trips is proposed to be discontinued during this work plan due to adequate coverage from other agencies sampling the slough at RM -12, hot spots, by the dam, and other fixed and random sites throughout the Lees Ferry reach.

Research Question I.1.1. What is the Species Composition, Relative Abundance, Longitudinal Distribution, and Population Trends of the Native and Nonnative Fish Community Inhabiting the CRe?

The primary objective of Project Element I.1 is to determine the species composition, relative abundance, and trends of fishes in the CRe, which is sampling that has occurred since 2000 (Figure 1). The methods for this project are explained in detail in AGFD Annual Reports (Boyer and Rogowski, 2020; Fonken and others, 2023). 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 meters (m) in length on both sides of the river.

Sampling reaches are 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. Sample sites within reaches may be reduced for logistical reasons or due to poor water quality (e.g., turbidity) affecting capture probability. Trip length in the FY 2025-27 work plan will be increased from 13 nights to 15 nights to allow for more sampling and the inclusion of portable PIT tag antennas as an alternate gear type to increase detections of previously tagged fishes (see Project Element G.9).

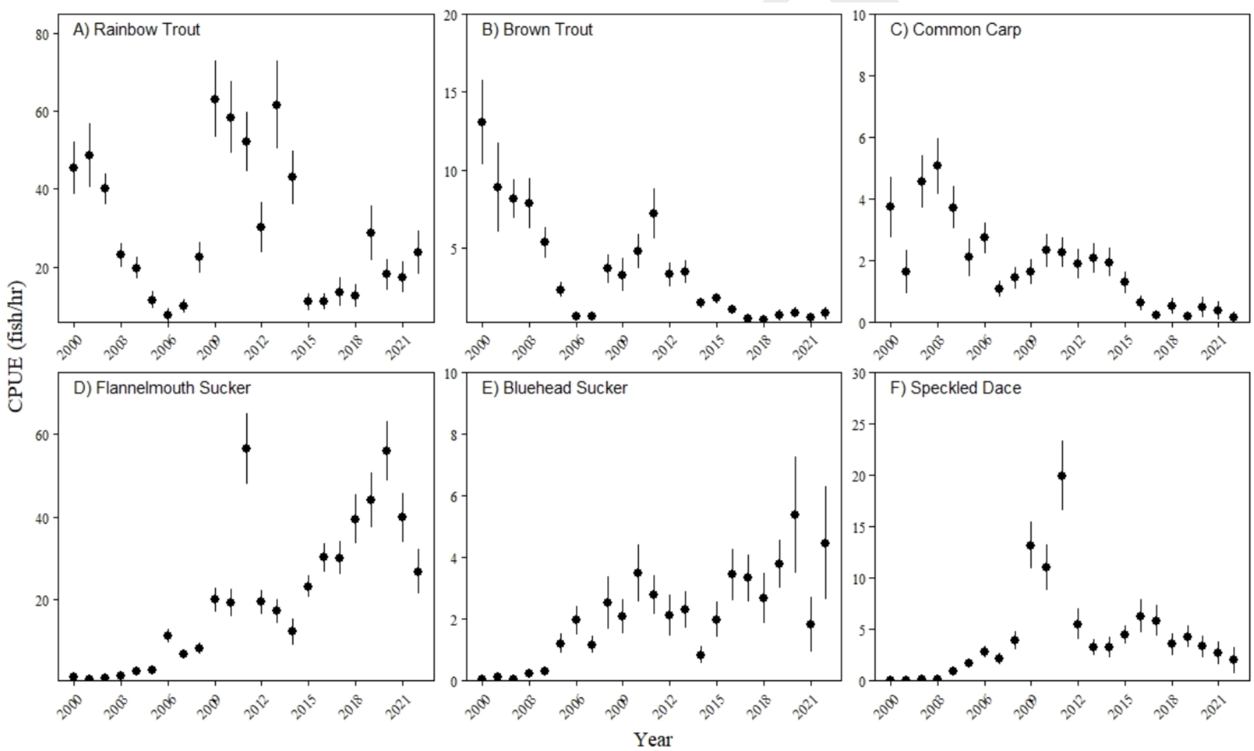

Figure 1. Mean electrofishing CPUE (# fish per hour) for nonnative (A-C) and native (D-F) fish species in the Colorado River from Lees Ferry to Pearce Ferry, from 2000-2022. Error bars indicate 95% confidence intervals (Fonken and others, 2023).

We will use a combination of standardized electrofishing, hoop netting, and catfish angling. 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.

Research Question: I.1.2. Can Portable Submersible PIT Tag Antennas be used to Detect Movement of Humpback Chub in Grand Canyon?

In the FY 2025-27 work plan we propose to test submersible portable PIT tag antennas in collaboration with Project Element G.9) with the objective of increasing detections of tagged fish in areas less frequently sampled in Grand Canyon. Increased detections could improve humpback chub population models by providing information on movement of humpback chub out of study reaches (vs. mortality), which may improve our understanding of apparent survival. Since AGFD samples random sites throughout Grand Canyon, deploying antennas will allow us to detect PIT-tagged fishes outside of fixed sites without handling them. Antennas will be deployed at a small number of sites (max 8-10) and left to passively read data while other sampling is taking place (e.g., hoop netting). In addition to potentially improving a humpback chub population dynamics model (see Project Element G.1), this information will supplement previous approaches by AGFD to visually assess movement using data from manual sampling and fixed antennas already deployed in Grand Canyon (Figure 2).

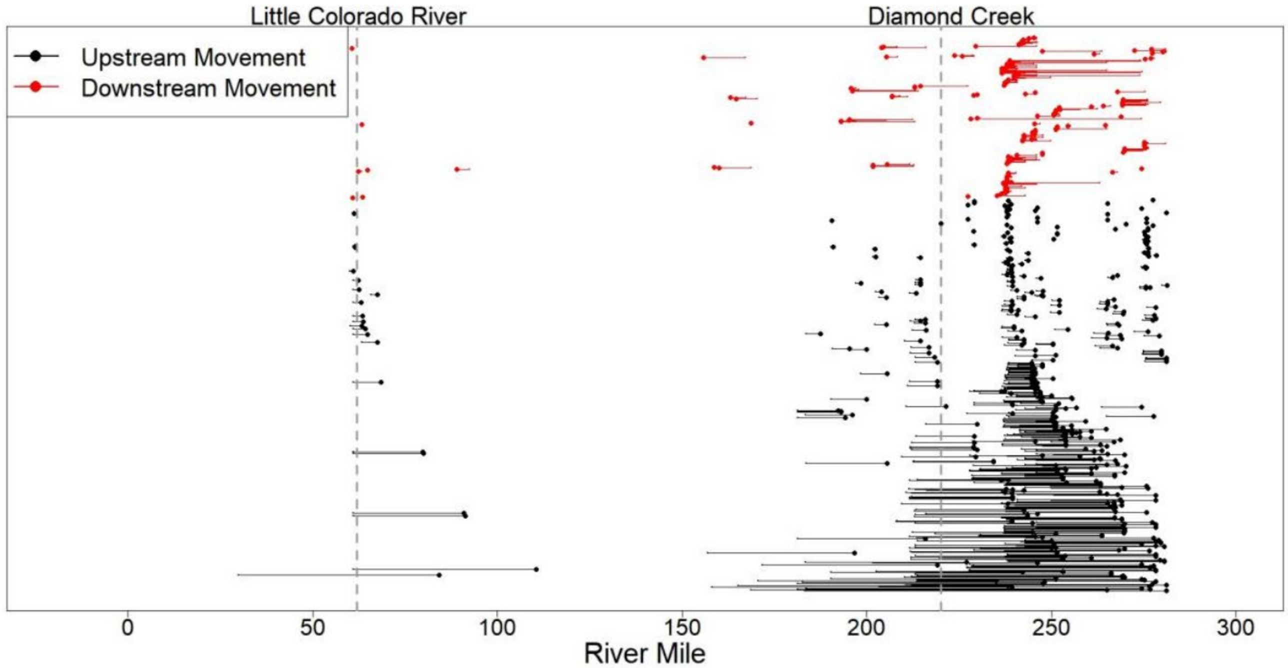

Figure 2. Movement of humpback chub (*Gila cypha*) tagged by AGFD and recaptured from manual sampling and from antennas deployed in Grand Canyon from Lees Ferry (RM 0) to Pearce Ferry (RM 281). Lines represent individual fish that move upstream (black lines) and downstream (red) from the point of origin (dots) (Fonken and others, 2023).

Project Element I.2. Estimating Kinship and Spawner Abundance of Warm-Water Nonnatives

Megan Osborne[1], Thomas Turner[1], Charles Yackulic[2], Maria Dzul[2], Kimberly Dibble[2], Drew Eppehimer[2]

[1]University of New Mexico, The Museum of Southwestern Biology
[2]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

The objective of this project element is to use kinship genetic analysis to better understand the ongoing expansion of smallmouth bass into Grand Canyon, determine the extent to which juveniles are locally produced or entrained from the reservoir, and potentially estimate spawner abundance and survival for species being removed from the system. This work will provide important information on reproductive dynamics and larval sources for a high-risk species that has the potential to prey on ESA-listed species if it disperses downstream. These data will inform discussions of management strategies, current stage of invasion, and offramps as laid out in the Invasive Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023). Data on kinship and nest location, when paired with data on hatch dates (see Experimental Fund Project Element I.6) can provide information on the effectiveness of LTEMP SEIS Flow Experiments to disadvantage recruitment and survival of smallmouth bass (U.S. Department of the Interior, 2024).

These data could also be used with other data sources in the development of LTEMP Performance Metrics 10.5-10.8, which are focused on detecting the reproduction of low, medium, high, and very-high risk nonnative aquatic species downstream from Glen Canyon Dam.

Research Question I.2.1. What Proportion of Smallmouth Bass Captured Downstream from Glen Canyon Dam are Locally Produced or Entrained from Lake Powell?

Kinship analysis relies on genetic samples from individuals to provide estimates of the number of full siblings (same mother and father), half siblings (same mother or father), and other relationships (e.g., parent offspring pairs) (Städele and Vigilant, 2016). Given large enough sample sizes, kinship analysis can also be used to fit close-kin mark-recapture models that estimate spawner abundance and survival even when individuals are being removed from the population (e.g., for exploited populations, or in the case of smallmouth bass that are being actively removed) (Bravington and others, 2016; Waples and Feutry, 2022). Even if sample sizes are not sufficient for these types of estimates, kinship grouping (e.g., did most individuals derive from a small or large number of parent pairings) and spatial patterns in grouping (e.g., are most larval fish captured near the slough siblings or half-siblings [indicating local recruitment]; or do individuals removed from near the dam represent a greater number of parent pairings [suggesting entrainment]) could help to better clarify nest location for smallmouth bass, especially when combined with other ongoing studies using side scan sonar to search for nests, and deploying artificial nest substrate to attract nest-building males (pilot work in FY 2024).

This project element relies on samples collected during smallmouth bass removal efforts conducted by the NPS (GLCA and GRCA) and routine trout monitoring trips by AGFD and the USGS (Project Elements H.1, H.2). Per NPS permit, any smallmouth bass captured downstream from Glen Canyon Dam is removed, humanely euthanized via Institutional Animal Care and Use Committee (IACUC)-approved methods, and preserved in 95% ethanol for genetic, diet, and (if young enough) hatch date analysis. These specimens provide the source DNA from which kinship can be determined using genetic markers like microsatellites or SNPs. Microsatellite markers for smallmouth bass have been developed (Malloy, Jr and others, 2000), and this is a proven method to identify individual genotypes and their variation among individuals for other species of fish in the Southwest (Turner and others, 2009).

Research Question I.2.2. Is There Spatial Structure in Kinship and are there Hotspots with Higher Densities of Related Individuals?

This project also aims to understand whether there are hot spots of full siblings that could help managers pinpoint nest locations. In FY 2023, the Bureau of Reclamation funded pilot work outside the GCDAMP to understand the kinship of smallmouth bass removed in 2022 to determine how related individuals were to each other.

GCMRC sent genetic material from these smallmouth bass to collaborators (Drs. Megan Osborne and Thomas Turner) at the University of New Mexico, Turner Aquatic Conservation Lab to test whether analysis using microsatellite markers could provide estimates of relatedness among individual smallmouth bass. Preliminary analysis indicated there were 94 full sibling pairs, and most of those pairs were dispersed across sampling sites (Figure 3). While there was no broad evidence of spatial structure in kinship, a larger number of sibling pairs were found at RM -14.74 and -14.72 (Figure 3), which may suggest habitat conditions were more suitable in those locations. Most of the 2022 samples analyzed were collected near the dam, so information on parentage would provide greater clarity on whether there were many nests located close to the dam or if juveniles were entrained and survived passage through the penstocks.

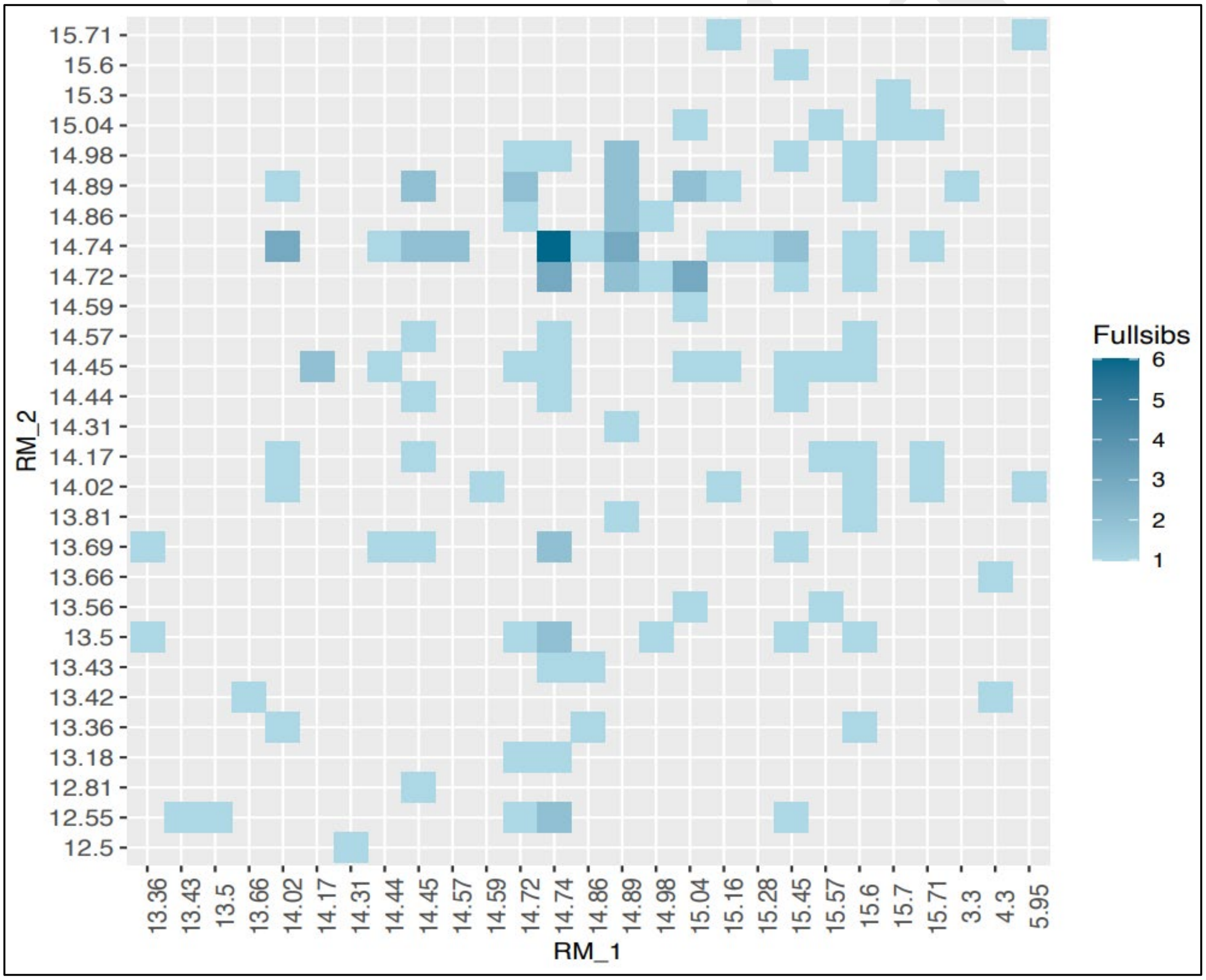

Figure 3. Count of total number of full siblings identified at each river mile pairwise comparison (blue squares). Deeper blue color indicates a larger number of pairs found at that RM comparison. Grey squares reflect zeros. Data do not indicate whether juveniles were produced in Lake Powell or downstream from Glen Canyon Dam (Huachan Liang, Thomas Turner, and Megan Osborne, University of New Mexico, unpublished, provisional data – do not cite).

Research Question I.2.3. How Many Parents Produced the Juveniles, and does Genetic Data Indicate Monogamous or Polygamous Mating in Smallmouth Bass?

Kinship analysis requires sampling of only one generation, whereas parentage analysis requires information from both the offspring and parents. Parentage analysis will provide data on how many pairs of adult smallmouth bass produced the juveniles (i.e., # of nests), and whether mating follows monogamous (Franckowiak and others, 2017) or polygamous relationships (i.e., full siblings vs. half siblings) that can affect the number of nests produced. Preliminary kinship data from 2022 with 192 samples from the Lees Ferry reach and 6 samples from Lake Powell indicated there were 94 unique full sibling clusters (indicating monogamy; Figure 3), and 5 half sibling pairs detected (indicating polygamy), but more data is needed beyond the initial year of sampling.

If guarding males are primarily monogamous and females typically only mate with one male, then there may be fewer opportunities for reproductive adults to build and maintain nests.

In 2022 and 2023 very few adults were captured in the Lees Ferry reach, and few samples were taken from the reservoir. This work would benefit from additional genetic sampling of parents and juveniles in Lake Powell near the arm near Glen Canyon Dam or in the forebay, as well as continued analysis of individuals captured through monitoring and removal efforts in the CRe. If this genetic technique is successful for smallmouth bass, we could expand this approach to other nonnative fish species with increasing catch rates (e.g., walleye).

Research Question I.2.4. How Comparable are Population Abundance Estimates using Close-Kin Mark-Recapture and Traditional Mark-Recapture using Green Sunfish as a Surrogate? Can we use Close-Kin Analysis to Obtain Accurate Estimates of Abundance for Species that must be Sacrificed/Removed from CRe?

Last, this element will explore the use of close-kin mark-recapture analysis to generate effective population size estimates for nonnative fish, even when those fish are being removed from the river (Bravington and others, 2016; Waples and Feutry, 2022). We propose to analyze genetic samples from green sunfish in the Lees Ferry reach using parentage and kinship analysis, and if possible fit close-kin mark-recapture models to compare estimates of abundance and survival to estimates from a concurrent traditional mark-recapture study. We would like to pursue this paired approach because it is difficult to obtain estimates of abundance with removal data, and we may not have enough statistical power to detect population change unless a management action leads to a large decrease in a nonnative fish species. Thus, using close-kin information may represent an innovative method to obtain abundances with removal data that could lead to improvements in model precision.

Close-kin mark-recapture models are still fairly novel within the broader field, so this comparison will help us better understand the potential to use this technique for other rarer species (e.g., smallmouth bass, walleye). The traditional mark-recapture analysis would rely on PIT-tagging and releasing green sunfish captured as part of the AGFD/TRGD project described in Project Elements H.1 and H.2.

Project Element I.3. Identifying Emerging Threats to the Colorado River Ecosystem Using Environmental DNA

Kimberly Dibble[1], Charles Yackulic[1], Thomas Franklin[2], Maria Dzul[1], David Ward[3], Bridget Deemer[1], Ian Bishop[1], Ted Kennedy[1], Justin Sanders[4], David Lytle[4], Terra Kelly[5], Eric Frye[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]U.S. Forest Service
[3]U.S. Fish and Wildlife Service
[4]Oregon State University
[5]EpiEcos

The objective of this project element is to conduct biosurveillance of nonnative species by collecting water samples and using molecular tools to identify high risk species of fish, crayfish, gastropods, and mollusks that are in the early stages of expansion or those that evade capture by traditional sampling techniques (National Park Service, 2021). All projects proposed in this element are intended to provide data to resource managers that could inform decision-making as it relates to the NPS Expanded Nonnative Species Management Plan (National Park Service, 2018, 2021) and the Invasive Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023). This includes deploying new technology in the Lees Ferry reach to automatically sample water on a set schedule to detect nonnative species, pairing eDNA data with traditional sampling gear to understand its sensitivity as a surrogate for detection and relative abundance data, estimating entrainment potential for high-risk species in Lake Powell, and monitoring Asian tapeworm and Lernaea parasites in humpback chub per the 2016 Biological Opinion (U.S. Department of the Interior, 2016a).

These data could also be used with other data sources in the development of LTEMP Performance Metrics 10.1-10.4, which are focused on detecting the presence of low, medium, high, and very-high risk nonnative aquatic species downstream from Glen Canyon Dam. In addition, data from Experimental Fund Project Element I.5 can provide smallmouth bass detection data to inform planning and evaluation of the effectiveness of LTEMP SEIS Flow Experiments to disadvantage recruitment and survival of smallmouth bass (U.S. Department of the Interior, 2024).

Research Question I.3.1. What High-Risk Species in Lake Powell are Moving into the Colorado River Undetected by Traditional Sampling Techniques?

Responding quickly to nonnative species introductions before populations become large and established is the least expensive and most effective way to control nonnative species (Leung and others, 2002). Environmental DNA has become a reliable and cost-effective tool that resource managers can use to detect rare nonnative species prior to population expansion (Pilliod and others, 2013; Klymus and others, 2015; Lacoursiere-Roussel and others, 2016; Pochardt and others, 2020, Spear and others, 2021, Yates and others, 2021; Rourke and others, 2022). In aquatic environments, fish continually 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 DNA can be extracted from cells collected in the environment in which an organism lives, rather than directly from the animals themselves (Pilliod and others, 2013; Klymus and others, 2015; Sepulveda and others, 2019). This reduces or eliminates fish handling and stress (can be a concern for non-target species) and allows managers to detect species at the early stages of expansion, species with low susceptibility to capture, or species residing in habitat areas outside of the range of standard sampling methods.

The warm-water nonnative aquatic species currently present in the Colorado River are only a fraction of the potential nonnative fish species that could establish, especially if fishes continue to be entrained from Lake Powell into warming Colorado River waters. New, emerging threats to the CRe, such as new nonnative species, parasites, or disease, also have the potential to affect fish and wildlife populations and human health. In the FY 2025-27 TWP, we propose to use automatic sampling technology to collect water samples to screen for emerging threats to the CRe. This will include use of an eDNA Autosampler (Smith Root; https://www.smith-root.com/services/training/environmental-dna-field-sampling-techniques) to automate sample collection in the field, which will allow us to 'catch' aquatic nonnative species year-round every few days even when trips are not on the water. The autosampler will be deployed in an area known to be a hot spot for nonnative species (e.g., downstream from dam, in slough), and samples will be retrieved every two to four weeks. Self-preserved filters will be extracted and analyzed in a controlled laboratory setting using high-throughput quantitative Polymerase Chain Reaction (qPCR), a highly sensitive method that can detect small amounts of DNA in the water column.

Filtered samples will be run using a new Aquatic Invasive Species (AIS) biochip developed by the U.S. Forest Service National Genomics Center, which will allow for quantitative, species-specific screening of very high risk or high-risk species that reside in Lake Powell (National Park Service, 2018, 2021). The AIS biochip currently contains 42 of the most problematic nonnative species in the western United States but is planned to be refined in FY 2025 to focus on species most concerning to managers in the Colorado River. Should we detect a new species, or expanded coverage of an existing known species, we will provide this information to GLCA, GRCA, and AGFD for management purposes.

These extracted samples can be stored as a library for decades, so as technology develops more data can be obtained from the samples over time (e.g., develop time series, conduct deeper sequencing/kinship analysis, or facilitate collaboration on other questions).

While qPCR will not occur in the field using this instrument, technology is improving rapidly, and this instrument represents a step towards automated sampling and processing in the field. If deployed, this autosampler will be part of a network of pilot eDNA autosamplers that will be installed in the Colorado River basin starting in summer 2024 as part of the USGS Rapid environmental (e)DNA Assessment and Deployment Initiative & Network (READI-Net). This pilot initiative aims to accelerate the use of eDNA as a best practice for the early detection of aquatic biological threats and delivery of tools and strategies to resource managers.

Research Question I.3.2. How Comparable are eDNA Methods to Traditional Sampling Gear for Detecting Sources and Dispersal of Nonnative Fishes in the Colorado River? In Comparison to Currently Used Methods, how Effective and Feasible is using eDNA Techniques to Monitor Changes in Distribution and Relative Abundance of the Fish Assemblage in Relation to Dam Operations and Environmental Conditions in the CRe?

A second objective of Project Element I.3 aims to increase biosurveillance of nonnative aquatic species throughout the Colorado River and its tributaries. We also wish to determine the degree to which eDNA sampling is comparable to traditional sampling methods in a large river system and identify its limitations and challenges at this phase in the technology's development. If this method is successful (either now, or with further development), it could be used to target locations for nonnative fish sampling, reduce the amount of hands-on sampling, and/or reduce the number of trips on the water by using automated eDNA sampling to track the distribution and relative abundance of fishes in the CRe.

In 2021 and 2022, GCMRC leveraged outside funding to collect eDNA samples from throughout the river corridor and in major tributaries. We were successful in detecting smallmouth bass, walleye, channel catfish, brown trout, green sunfish, and razorback sucker and/or razorback/flannelmouth sucker hybrids using eDNA. However, key questions remain in how comparable this molecular tool is to detecting fish captured using traditional sampling gear, and whether estimates of relative abundance (using eDNA copy number [concentration]) are comparable to catch rates for native and nonnative species (Pilliod and others, 2013; Lacoursiere-Roussel and others, 2016; Pochardt and others, 2020; Spear and others, 2021; Yates and others, 2021; Rourke and others, 2022). We seek to provide clarity on that question in the FY 2025-27 work plan by collecting eDNA samples in tandem with regular monitoring trips. The cost of eDNA sampling (salary, logistics, travel, operating expenses, analytical costs) is incurred in Project Element I.3 and not in the projects below.

Seining backwaters in the mainstem Colorado River (funded in FY 2025 only)

Project Element G.5 adds an additional backwater seining boat to the Fall USFWS Humpback Chub Aggregations Monitoring trip to search for nonnative species utilizing backwaters during the warmest month of the year. The purpose of this work is to determine whether we are fully cataloging nonnative species that utilize warm, isolated habitats throughout the canyon. If these data indicate there are species evading capture through seining, it could lead to a revision of the seining strategy used to capture fish in backwaters. These samples will also be used to determine whether smallmouth bass are utilizing backwaters in Grand Canyon National Park, which has direct management implications. We plan on collecting up to 100 eDNA samples from paired backwater seining sites in FY 2025.

*Seining pools in the upper Little Colorado River drainage (**proposed as unfunded at this time**)*

Project Element G.8 monitors spring-fed pools in Piute Canyon in the upper LCR drainage to understand the extent to which humpback chub utilize these pools (and under what hydrologic conditions), as well as identify sources of nonnative species that could be flushed downstream into the LCR during monsoon season. Detection of very high or high-risk nonnative fishes could lead to Tribal management efforts. We plan on collecting three replicate samples from each paired LCR pool site in FY 2025.

Electrofishing in the Lees Ferry Reach

Project Element H.2 monitors the rainbow and brown trout population in the Lees Ferry reach through the Trout Reproductive and Growth Dynamics (TRGD) project, which will be combined with the AGFD trout monitoring project in this work plan (Project Element H.1). The purpose of this sampling is to compare species detection and relative abundance in sites 1A & 1C by deploying a separate eDNA boat to passively collect water samples in each 250-m reach while electrofishing is occurring. We plan on collecting three replicate samples from 48 reaches split between the upper site (1A) and lower site (1C) during a trip in FY 2026.

Electrofishing, hoop netting, and antennas in the mainstem Colorado River

Project Element I.1 collects system-wide native and nonnative fish monitoring data at random sites located from Lees Ferry to Pearce Ferry. The fish taxa change drastically throughout Grand Canyon, with trout dominating the catch near the dam and native fish dominating in western Grand Canyon. The purpose of this sampling is to compare the fish detection and relative abundance (copy number) data to catch data collected during electrofishing, hoop netting, and passive antenna sampling. We plan on collecting one sample per reach during electrofishing operations (so as not to delay the pace of sampling) and one sample per reach near deployed hoop nets or portable antennas during a trip in FY 2027.

Research Question I.3.3. How do the Biophysical Characteristics of Lake Powell Affect the Likelihood of Nonnative Fish Entrainment through Glen Canyon Dam?

A third objective of I.3 aims to understand how the biological and physical aspects of Lake Powell affect the likelihood that high-risk nonnative fish will be entrained through the penstocks of Glen Canyon Dam and deposited into the river below. This element builds off previous work recently funded by Reclamation that used traditional sampling gear (gill nets, minnow traps, Ichthyoplankton tows, light traps) combined with acoustic telemetry and hydroacoustic surveys to characterize the fish community at depth inhabiting the forebay, confluence, and Wahweap in 2022 and 2023. This sampling occurred over eight sampling events when the reservoir was mixed in winter and stratified from late spring to early fall. Notably, the authors found that 99% of the fish fauna in the Lake Powell forebay was nonnative, and the depth of the epilimnion increased during large inflow years, which increased the probability of occupancy at depth for species such as smallmouth bass. However, smallmouth bass tended to occupy shallower depths in the epilimnion than species such as channel catfish (Barrett Friesen, unpublished data).

This study noted that additional avenues of research could comprehensively describe the threat of entrainment by releasing PIT-tagged fish in the forebay at the depth of the penstocks to track survival and movement of tagged fishes downstream. They noted additional hydroacoustic surveys are a cost-effective method to determine fish sizes and densities during years in which the epilimnion is close to the penstocks, which could be used to monitor entrainment-likely fishes. Last, the authors indicated they did not capture large schools of suspected threadfin shad seen in hydroacoustic surveys via gill nets, but this could be accomplished using trawl nets in the Forebay to confirm species identity (Barrett Friesen, unpublished data).

In the FY 2025-27 work plan, we propose to build off this previously funded work by collecting eDNA samples in parcels of water at depth in the Forebay with a Van Dorn sampler, which is used for Lake Powell water quality monitoring and is designed to take samples in lakes and stratified water bodies. We plan to base our depths of sampling on distinct zones of water quality that develop within the reservoir based on reservoir elevation and inflows, including the depth of chlorophyll max, dissolved oxygen min, the photosynthetically active radiation zone, and water temperature (Figure 4). We will account for movement of water at depth due to the seiche (internal wave) by estimating the period of the seiche and sampling at the same point within each wave. Further, we plan on sampling during the day and at night to capture variation in penstock-entrainable fishes in the lower epilimnion due to diel migration of zooplankton. During daylight hours zooplankton descend to the bottom of the photic zone to avoid predation by sight-seeing predators, but ascend to the warmer, more nutrient and prey-rich surface layers at night to feed when the predatory threat decreases. We hypothesize that forage fishes and their predators (e.g., smallmouth bass) may descend into deeper depths early in the morning as they follow their food source deeper into the reservoir, potentially leading to higher levels of entrainment at different times of the day.

We propose to sample 1-2m from the surface, top of chlorophyll max (~5m), bottom of chlorophyll max/DO min (~15m), above the penstocks (~25m, depending on elevation), at the penstocks, and below the penstocks in increments of 10m (e.g., ~35 and 45m; Figure 4). We will sample both bank (slope) and thalweg locations during spring (April) and fall (August/September) in FY 2026, when the reservoir is stratified. These data will be paired with eDNA samples taken from penstock water and from the base of the dam. This sampling approach could be paired with ongoing pilot studies to examine entrainment including future hydroacoustic surveys and/or tagged fish released in the Forebay near the penstocks. This project is intended to provide information to the USBR that could inform management actions related to curtailing nonnative fish passage through the penstocks per the 2016 Biological Opinion (e.g., thermal curtain, fish exclusion barrier net in Lake Powell, tucker trawl net downstream from Glen Canyon Dam).

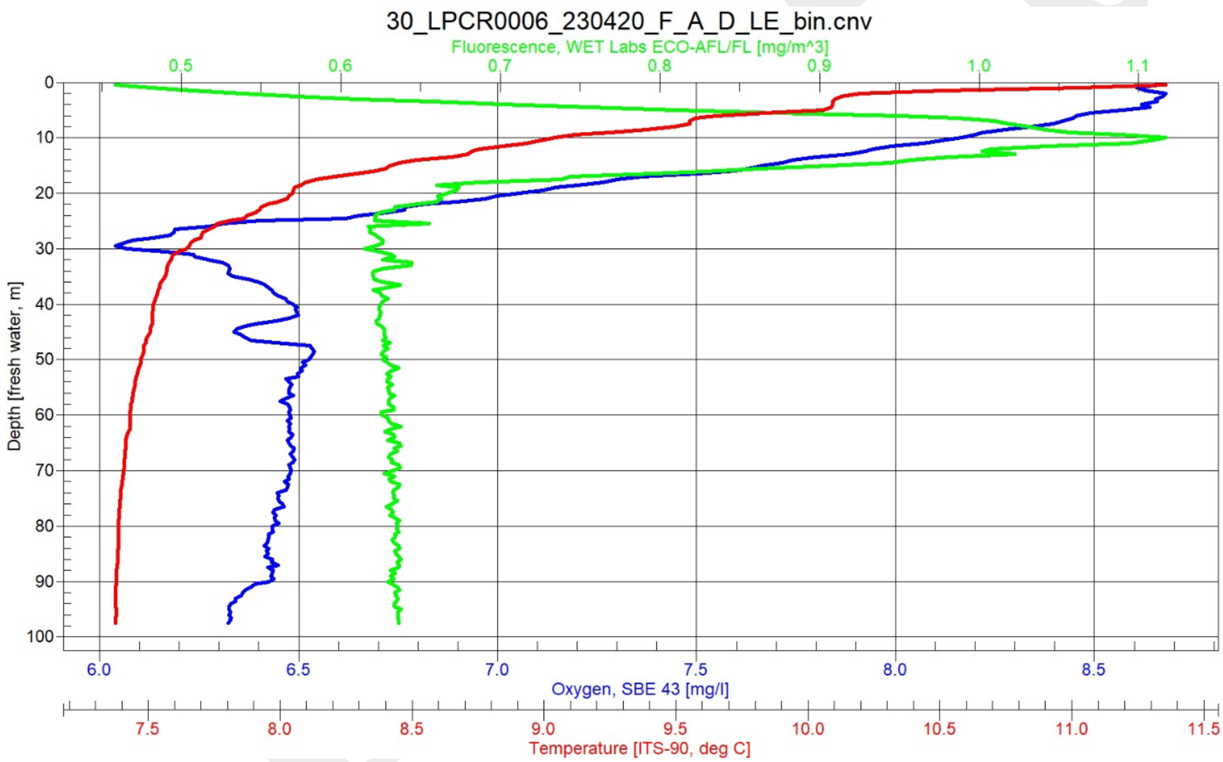

Figure 4. Water quality profile at depth in the forebay of Lake Powell in April 2023 showing chlorophyll (florescence, in green), dissolved oxygen (blue), and water temperature (red) as an example of our approach to selecting sampling depths (Bridget Deemer, USGS, unpublished, provisional data – do not cite).

Research Question I.3.4: What is the Incidence of Parasite Infestation in Humpback Chub in the Little Colorado River and Mainstem Colorado River? Can a Molecular Assay be Developed to Reduce Handling Time and Expand the Scope of Monitoring?

The fourth objective of Project Element I.3 is to continue to monitor Asian fish tapeworm (*Bothriocephalus acheilognathi*) and anchor worm (Lernaea) in humpback chub as specified in the Environmental Commitments Section in the LTEMP ROD (and 2016 Biological Opinion) (U.S. Department of the Interior, 2016a, b). To date, Asian fish tapeworm monitoring has been conducted periodically in the Little Colorado River and in the mainstem Colorado River by the USGS in collaboration with USFWS (Figures 5a, 5b), and anchor worm presence has been recorded through exterior visual inspection of fish on USFWS, USGS, NPS, and AGFD fish trips.

In the FY 2025-27 work plan, we propose to continue periodic monitoring to assess infestation of parasites in humpback chub via traditional sampling methodology, but we propose to develop a molecular assay to detect the presence of those parasites in water and fish fecal matter, and then test the sensitivity and selectivity of the assay using a paired cross-over study (**molecular assay development and cross-over sampling is proposed as unfunded in this draft of the work plan**).

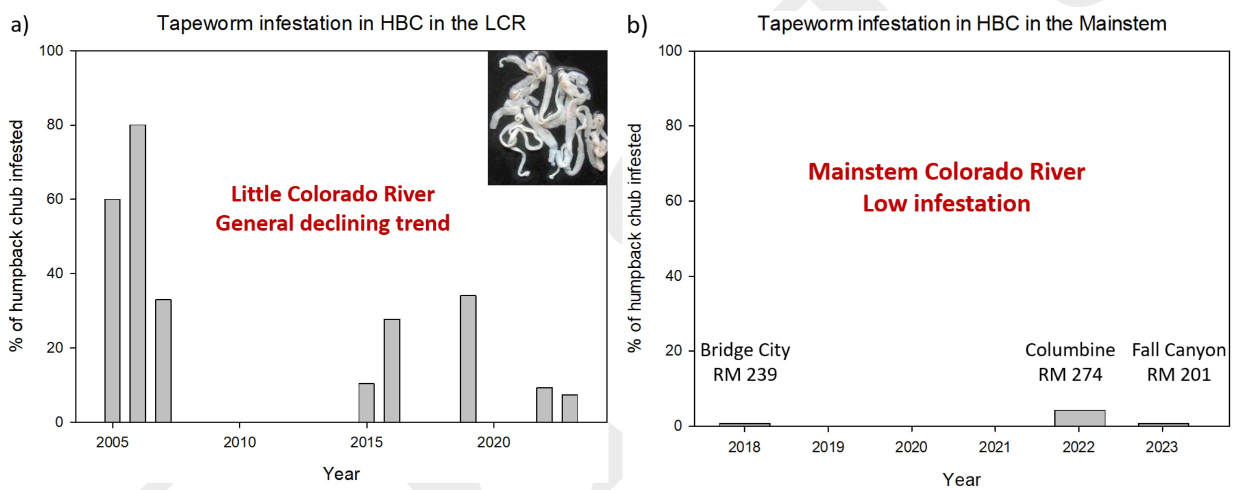

Figure 5. Proportion of humpback chub, *Gila cypha*, infected by Asian tapeworm in the Little Colorado River (a) and in the mainstem Colorado River (b) from 2005-2023 based on periodic sampling (David Ward, U.S. Fish and Wildlife Service, unpublished, provisional data – do not cite).

Traditional sampling methodology

Asian fish tapeworm is a nonnative species that infests warm-water cyprinid fish. This parasite has been identified as one of six potential threats to the continued existence of endangered humpback chub (U.S. Fish and Wildlife Service, 2002), as 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 the condition of adult humpback chub from the LCR (Meretsky and others, 2000), but was more rare in the mainstem due to cold water temperatures (Hoffnagle and others, 2006). Periodic monitoring for the presence of this parasite commenced in 2005 and the proportion of humpback chub infested with tapeworm in the LCR has generally declined over time (Figure 5a).

Infestation of humpback chub in the mainstem CRe has been comparatively low in western Grand Canyon and only recently sampled (Figure 5b). Asian tapeworm and anchor worm monitoring will continue in this work plan as specified in the 2016 Biological Opinion (U.S. Department of the Interior, 2016a) in collaboration with the USFWS (Project Elements G.2, G.5) and on JCM-East and JCM-West trips (Project Elements G.3, G.6). Briefly, approximately 40 humpback chub will be captured and placed in separate containment baskets on the banks of the river for 48 hours while they are being treated with a bath of Praziquantel, which triggers them to expel Asian tapeworm. Individual worms will be collected from baskets and % of humpback chub infested calculated. Lernaea will be visually identified in the field and recorded by all fish trips on the water.

*Proposed molecular sampling methodology (**proposed as <u>unfunded at this time</u>**)*

We propose to collaborate with Oregon State University (Dave Lytle and Justin Sanders labs) to develop molecular assays for Asian tapeworm and Lernaea. These assays would be used to test water and fecal eDNA samples from humpback chub to determine presence and infection intensity of parasitized fish. This assay would need to be sensitive enough to detect actual infestation of the definitive host (fish), rather than infestation of the intermediate host (copepods) consumed as a diet item during its procercoid life stage. We envision a cross-over study using fish treated with Praziquantel but also tested/swabbed for the eDNA of parasites. If successful, moving to molecular-based methods would allow for more efficient sampling, less stress to the fish, more information, and the ability to collect samples throughout the canyon (not just in one or two spots). Asian tapeworm requires a temperature of >20°C to mature, and anchor worm requires >17°C, so a good understanding of where parasitic load is highest may help us anticipate changes in parasitism if the Colorado River continues to warm.

Project Element I.4. Modeling Population Dynamics and Improving Forecasting Tools for Smallmouth Bass and Other Nonnative Fishes

Charles Yackulic[1], Drew Eppehimer[1], Kimberly Dibble[1], Maria Dzul[1], Brian Healy[1], Eric Frye[1], Kate Behn[1], Lindsay Hansen[1], Ben Miller[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

The objective of this project element is to focus on modeling nonnative fish data and reporting results to GCDAMP stakeholders, combined with laboratory work to understand how turbidity influences growth (through energy assimilation) and survival of smallmouth bass. Modeling projects in this project element include updating forecasting tools for smallmouth bass [if new data or information is available that may improve models], evaluating the effectiveness of management actions including LTEMP Experimental Flows (U.S. Department of the Interior, 2024) on smallmouth bass growth, catch rates, dispersal, and recruitment, and developing a workflow process for an occupancy model that evaluates data from Projects H, G, and I to report on a standard set of LTEMP Performance Metrics that evaluate the presence and reproduction of nonnative aquatic species (Resource Goal #10).

This project element also supports laboratory trials to determine the effects of turbidity and water temperature on the growth and survival of early life stages of smallmouth bass and other nonnative fishes, which is data that may be used to update the smallmouth bass population growth model (Eppehimer and others, 2024). Last, this element allocates time for a GCMRC Research Fish Biologist to lead development of a science plan to support data collection for smallmouth bass sampling and removals in the Lees Ferry reach, and provides time to analyze nonnative fish data, communicate findings to GCDAMP stakeholders, participate in Rapid Response Tech Team bi-weekly calls, and provide science to support discussions of offramps laid out in the Invasive Fish Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023).

I.4.1. How does Turbidity and Temperature Affect Feeding Efficiency and Survival of Early Life Stages of Smallmouth Bass? How does Adding Turbidity as a Parameter in the Smallmouth Bass Population Growth Model Affect Performance?

The first objective of Project Element I.4 is to determine how turbidity, temperature, and the presence of predatory fish affect energy consumption by early life stages of smallmouth bass in laboratory feeding trials. Smallmouth bass are visual predators that can effectively forage in clear water (Brown and others, 2009), but higher turbidity and total suspended solids in the water column downstream from the Paria and Little Colorado rivers have the potential to decrease foraging efficiency and increase mortality, particularly for early life stages (Sweka and Hartman, 2003; Suedel and others, 2017). High turbidity near the Little Colorado River has been measured at a level known to affect foraging in other sight-feeding predators (Yard and others, 2011), but smallmouth bass in the upper basin have successfully invaded turbid river reaches and have had population-level effects on native species (e.g., Dibble and others, 2021; Martinez and others, 2014).

This laboratory study seeks clarification on whether turbidity in the Colorado River could limit downstream dispersal and growth of this aquatic nonnative species. This work will directly inform any potential updates to the smallmouth bass population growth model developed by Eppehimer and others (2024). The current model assumes water temperature is the key factor influencing the smallmouth bass population growth rate (i.e., through spawning timing/occurrence, age-0 fish growth, and age-0 fish survival) and is currently being used to forecast population-level responses under different reservoir operations (Eppehimer and others, 2024). However, this model could be modified to add turbidity if it has a strong effect on early life stage growth and survival.

I.4.2. How Effective are Management Actions (LTEMP Flow Experiments, Removals) at Reducing Smallmouth Bass Population Growth, Survival, Dispersal, and Reproduction?

The second objective of Project Element I.4 is to evaluate whether management efforts to reduce smallmouth bass catch rates, dispersal, growth, reproduction, and recruitment through removals and/or LTEMP Flow Experiments are working as designed. In the FY 2025-27 work plan, we will analyze nonnative fish data provided by federal and state partners (e.g., AGFD, NPS, USFWS) that are compiled into a single nonnative fish spreadsheet. Analysis of these data will vary by research question, but we will calculate catch-per unit effort and possibly use close-kin mark-recapture analysis (I.2) to determine whether the smallmouth bass population is increasing in GLCA and GRCA (Figure 6).

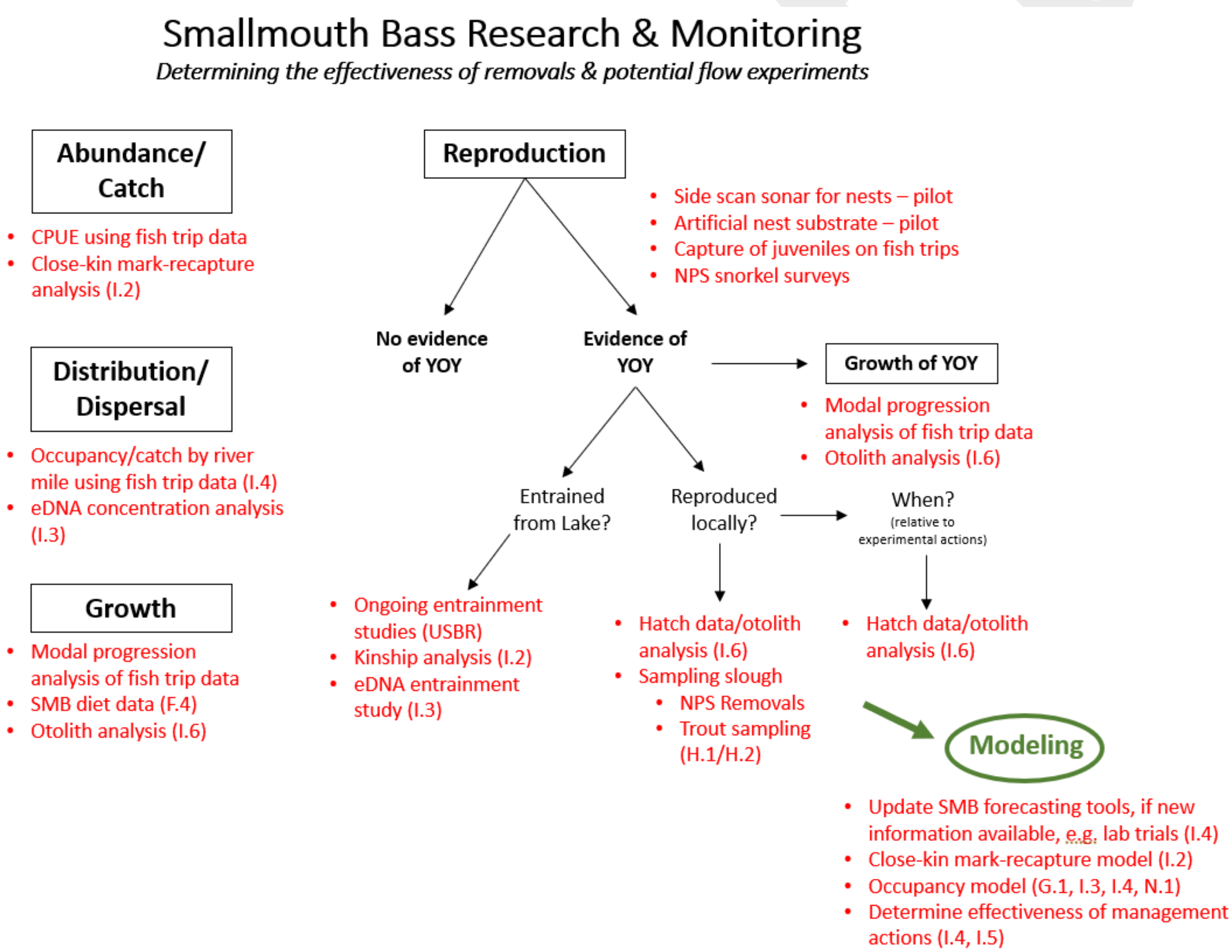

Figure 6. Flow diagram of planned smallmouth bass research and monitoring studies by Project Element (in parentheses) that provide data and analyses for examining the effectiveness of removals and potential LTEMP Flow Experiments on smallmouth bass catch, dispersal, growth, reproduction, and recruitment (Diagram courtesy of Charles Yackulic and Kimberly Dibble, USGS).

We will evaluate dispersal using detection data by river mile using traditional sampling gear and eDNA/water sampling (I.3) and calculate growth rates via modal progression analysis (Figure 7). Smallmouth bass diet data will provide insight into predation pressure at various life stages (F.4). Reproduction and recruitment will be evaluated using pilot data from side scan sonar to search for nests, by deploying artificial substrate to attract nest-building males, capture of larvae or juveniles on fish trips, and using information from NPS snorkel surveys. If there is evidence of age-0 fish, kinship analysis (I.2), hatch date analysis (I.6), entrainment studies (e.g., I.3), and targeted hot spot sampling will provide information on whether larvae were produced locally or if they were entrained from Lake Powell (Figure 6). A data visualization dashboard (mapping tool) to view nonnative fish data was piloted in 2023 resulting from a collaboration between Reclamation and GCMRC (Project K). In this work plan, Project K plans to continue to refine that data visualization tool and share it with the public and GCMRC stakeholders.

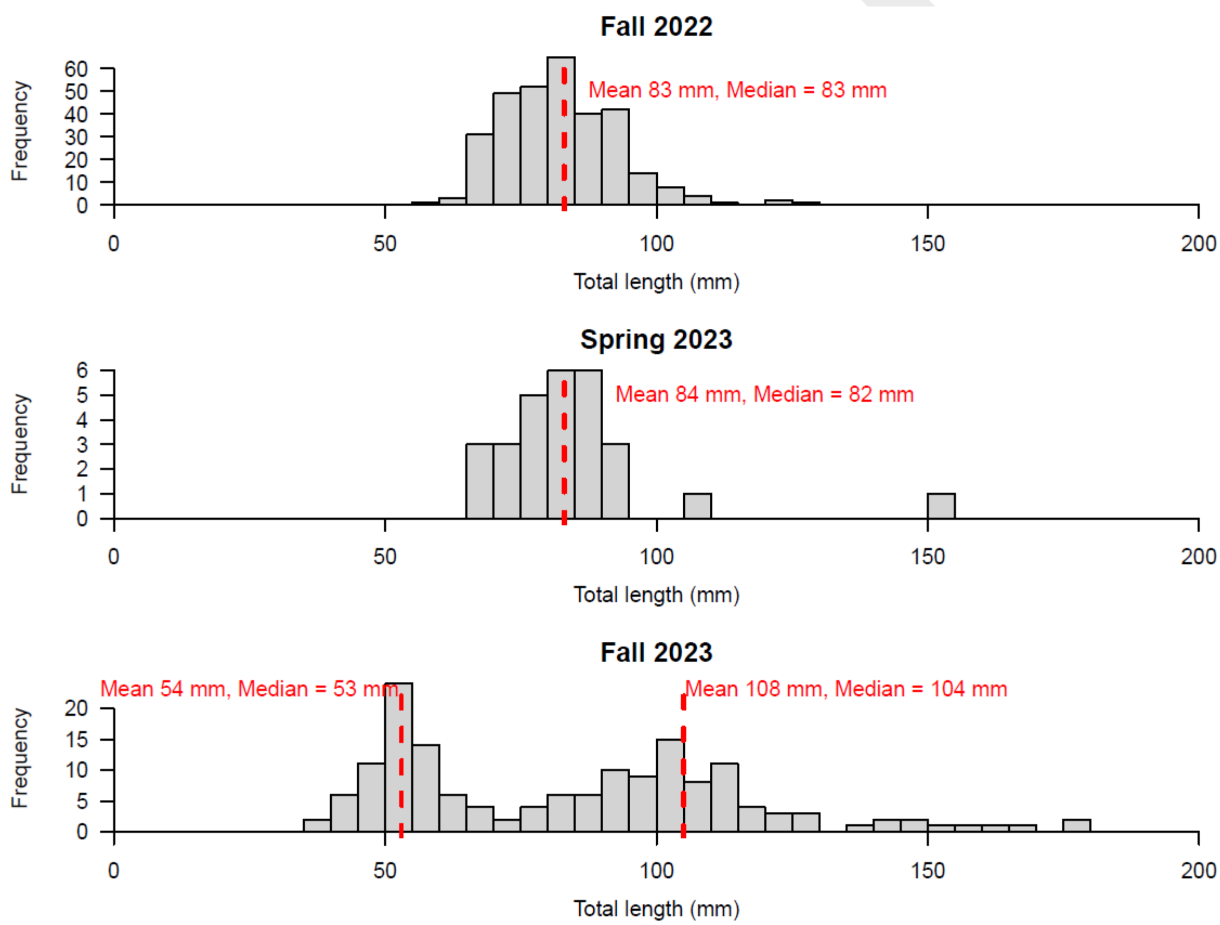

Figure 7. Length-frequency histograms of smallmouth bass that can be analyzed using modal progression analysis to calculate growth rates. Growth from fall 2022 to spring 2023 was minimal due to cold winter temperatures. Temperatures in 2023 were colder overall than in 2022, so age-0 fish did not grow as fast (mean=83mm in fall 2022; mean=54mm in fall 2023) (Figure provided by Charles Yackulic using data from NPS, AGFD, and USGS; unpublished, provisional data – do not cite).

Collectively, the analysis and visualization of multi-agency nonnative fish data described in Project Element I.4 will be used to support discussions of monitoring effectiveness and offramps laid out in the Invasive Fish Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023). Additional LTEMP SEIS-related work is included as options to be funded by the Experimental Fund.

We propose to use eDNA to evaluate presence and dispersal of smallmouth bass DNA from the dam to the Little Colorado River confluence prior to and after the flow (I.5) and evaluate hatch dates of fish to determine if smallmouth bass were produced before, during, or after LTEMP SEIS flow implementation (I.6).

I.4.3. What are the Long-Term Drivers of Distributional Changes in Native and Nonnative Fishes in the CRe?

The third objective of Project Element I.4 is to develop a workflow process for an occupancy model that evaluates existing monitoring and research data from Projects H, G, and I to report on a standard set of LTEMP Performance Metrics. The proposed metric for Resource Goal #10 includes eight metrics (or two metrics with four sub-categories) based on categories of nonnative species risk (GCNP, 2013; NPS, 2018, 2021). Metrics 10.1-10.4 are based on detection (average number) of low, medium, high, and very-high risk nonnative species, while Metrics 10.5-10.8 are based on evidence of nonnative species reproduction for those same risk categories. Data on detections from AGFD, NPS, USFWS, USGS, and other cooperators (e.g., BioWest/ASIR) can be used as data in the development of this occupancy model (see Project Elements G.1, H.2, N.1).

Outcomes and Products

Project Element I.1.

Outcomes

- Monitoring and detection of trends in distribution and relative abundance of native and nonnative fishes in the Colorado River. Evaluation 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, 1-2 peer reviewed journal articles by AGFD during this work plan on issues related to Colorado River fishes.

Project Element I.2.

Outcomes

- Estimation of the number of smallmouth bass nests that originated in the Lees Ferry reach or in Lake Powell. Estimation of sibship, parentage, and genetic diversity in juvenile smallmouth bass. Determination of monogamous or polygamous mating, which could affect overall number of nests maintained. Use of close-kin mark-recapture analysis to estimate spawner abundance and effective population size in smallmouth bass and green sunfish (the latter will be compared to traditional mark-recapture analysis).

Products

- Manuscript describing smallmouth bass reproductive dynamics, including information on sibship, parentage, mating strategies, and estimates of spawner abundance and effective population size.
- If genetic data show promise, manuscript describing close-kin mark recapture analysis, paired with traditional mark-recapture analysis to estimate population size/abundance for green sunfish, and its potential use for smallmouth bass and walleye.
- Manuscript describing development of genetic markers (microsatellites) for green sunfish genome to conduct close-kin mark-recapture analysis.
- Presentation of results at Annual Reporting Meetings and at a scientific conference.

Project Element I.3.

Outcomes

- Refinement of Colorado River-specific high-throughput qPCR biochip for Aquatic Invasive Species known in Lakes Powell and Mead. Continuous monitoring of high-risk nonnative species in the Lees Ferry reach on a set schedule using an eDNA autosampler. Expanded detection capability for nonnative species from Glen Canyon Dam to Pearce Ferry, with cross-over comparison of detection and relative abundance data from traditional and eDNA sampling methods. Improved understanding of entrainment potential for nonnative species in Lake Powell. Estimation of parasite infestation and load in humpback chub in the Little Colorado River and mainstem Colorado River.

Products

- Manuscript describing results from pilot project to deploy eDNA autosampler in the Lees Ferry reach. This manuscript will include an analysis of detection data in each month of the year in FY 2025 that will refine future deployment schedules.
- Manuscript describing results from paired eDNA and traditional sampling year study, which includes seining, electrofishing, hoop netting, and antennas.
- Manuscript describing detection of aquatic nonnative species DNA at depth in Lake Powell relative to the penstocks, to provide greater understanding of what species might be entrained relative to Lake Powell biophysical characteristics.
- Analysis of humpback chub parasite infestation data for Annual Reporting Meeting, or manuscript describing parasite detections using Praziquantel vs. development of molecular markers (***proposed as unfunded at this time***).
- Presentation of results at Annual Reporting Meetings and at a scientific conference.

Project Element I.4.

Outcomes

- Estimation of smallmouth bass early life stage feeding efficiency and survival under turbidity conditions expected in the Colorado River during pre- and post-monsoon periods. Potential update to forecasting model for smallmouth bass based on results from turbidity trials. Determination of the effectiveness of management actions for reducing smallmouth population growth, survival, dispersal, and reproduction. Development of occupancy model for LTEMP Performance Metric for Resource Goal #10.

Products

- Manuscript describing results from laboratory experiments on the effects of turbidity on smallmouth bass feeding efficiency and survival. Potentially updated forecasting model for smallmouth bass population growth.
- Manuscript describing effectiveness of LTEMP Flow Experiments and removals on smallmouth bass catch rates, growth, dispersal, and reproduction.
- Manuscript describing occupancy model for native and nonnative fish using data collecting from routine monitoring efforts across Projects H, G, and I.
- Presentation of results at Annual Reporting Meetings and at a scientific conference.

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Budget

Fiscal Year 2025									
Project I Non-native Invasive Species Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
I.1. System-wide native fishes and invasive aquatic species monitoring	$8,661	$0	$3,100	$103,855	$217,550	$0	$31,731	**$364,897**	
I.2. Estimating kinship and spawner abundance of warm-water non-natives	$67,051	$0	$200	$0	$140,445	$0	$18,874	**$226,570**	
I.3. Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$92,592	$2,150	$31,685	$1,050	$63,504	$0	$29,695	**$220,676**	
I.4. Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$174,691	$200	$1,800	$0	$0	$0	$38,519	**$215,210**	
Total Project I	**$342,996**	**$2,350**	**$36,785**	**$104,905**	**$421,499**	**$0**	**$118,819**	**$1,027,354**	**$50,797**

Fiscal Year 2026									
Project I Non-native Invasive Species Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
I.1. System-wide native fishes and invasive aquatic species monitoring	$7,140	$0	$3,100	$110,692	$217,550	$0	$33,857	**$372,339**	
I.2. Estimating kinship and spawner abundance of warm-water non-natives	$69,138	$0	$200	$0	$140,445	$0	$19,884	**$229,667**	
I.3. Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$125,727	$4,250	$3,700	$3,640	$74,844	$0	$33,279	**$245,440**	
I.4. Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$198,962	$2,200	$1,800	$0	$0	$0	$45,869	**$248,831**	
Total Project I	**$400,967**	**$6,450**	**$8,800**	**$114,332**	**$432,839**	**$0**	**$132,889**	**$1,096,277**	**$56,221**

Fiscal Year 2027									
Project I Non-native Invasive Species Monitoring and Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
I.1. System-wide native fishes and invasive aquatic species monitoring	$7,639	$0	$3,100	$114,150	$217,550	$0	$35,751	**$378,190**	
I.2. Estimating kinship and spawner abundance of warm-water non-natives	$73,978	$2,000	$200	$0	$140,445	$0	$22,039	**$238,662**	
I.3. Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$121,288	$150	$3,300	$15,266	$79,704	$0	$35,152	**$254,860**	
I.4. Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$212,889	$200	$1,800	$0	$0	$0	$50,284	**$265,173**	
Total Project I	**$415,794**	**$2,350**	**$8,400**	**$129,416**	**$437,699**	**$0**	**$143,226**	**$1,136,885**	**$59,843**

*GCDAMP Special Rate: Rate includes current DOI preferred rate (currently 15%; subject to change) and facilities rate (will vary annually). No USGS bureau overhead is charged (unique to the GCDAMP agreement).

**USGS Contributing Funds: The amount of funds required to cover the subsidy created by the reduced burden rate (i.e., GCDAMP Special Rate). As in previous years, SBSC/GCMRC will request these funds of the USGS cost-share program. These funds are not guaranteed.

Project J: Socioeconomic Research

Investigators

Lucas Bair[1], Josh Abbott[2], Pierce Donovan[3], Aaron Enriquez[4], Helen Fairley[1], Brian Healy[1], Kristin Hoelting[5], Brenna Jungers[6], Micheal Springborn[7], Charles Yackulic[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]Arizona State University
[3]University of Nevada, Reno
[4]U.S. Geological Survey, Fort Collins Science Center
[5]Social Science Research Consultant
[6]Mississippi State University
[7]University of California, Davis

Project Summary and Purpose

In the Long-term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) "recreational experience" and "Tribal resources" are goals that require social and economic monitoring and research to better understand the impacts of management actions related to the operation of Glen Canyon Dam (GCD) on these resources (U.S. Department of Interior, 2016). While there has been some initial monitoring and research related to these goals (Bair and others, 2016; Neher and others, 2017; Neher and others, 2018), there is a need for more comprehensive and long-term social and economic monitoring and research on these topics to adequately inform the Glen Canyon Dam Adaptive Management Program (GCDAMP). This project contains elements that aim to establish long-term monitoring and research that meet needs for the "recreational experience" and "Tribal resources" goals in the LTEMP EIS:

1) **Recreational Experience**: To support research and monitoring needs related to "recreational experience," this project element will improve monitoring and modeling of recreational access, participant behavior, and economic value, in collaboration with the National Park Service (NPS) and Arizona Game and Fish Department (AGFD), and

2) **Tribal Resources**: To support research and monitoring needs related to "Tribal resources," this project element focuses on improving integration of Tribal benefits knowledge, knowledge of benefits and well-being arising from ecosystems and human engagement with ecosystems, in the GCDAMP (Hoelting and others, 2024a). The effort supports increased recognition and comprehension of the diverse forms of Tribal benefits knowledge that are available to inform GCDAMP decision-making through multiple learning pathways. This effort will be carried out in collaboration and co-production with Tribal led monitoring activities to ground the conversation in Tribal research frameworks.

Related to monitoring and research and in support of goals in the LTEMP EIS, an objective in the LTEMP EIS is to "determine the appropriate experimental framework that allows for a range of programs and actions, including ongoing and necessary research, monitoring, studies, and management actions in keeping with the adaptive management process." The important phrase in this objective is the identification of necessary monitoring, research and management actions while keeping with the adaptive management process. To further this objective, this project includes an element to conduct research related to integrated modeling of biological, physical, and economic systems, with a focus on value of information (VoI) analysis. The latter effort improves the ability of GCDAMP to evaluate management actions and prioritize monitoring and research.

Science Questions

Integrated Models for Adaptive Management

- The value of information derived from monitoring and research in a multi-objective adaptive management program is partially dependent on management goals and the relative value of resources, when predicting outcomes of resource states from experimental management actions.

This hypothesis will be tested through continued development of predictive integrated resource models and formal value of information analysis.

Recreation Monitoring and Research

Recreation modeling

- The economic value of recreational angling at Lees Ferry in Glen Canyon National Recreation Area will decline over time with projected impacts of aridification in the Colorado River Basin.
- The economic value of recreational whitewater rafting on the Colorado River in Grand Canyon will decline over time with projected impacts of aridification in the Colorado River Basin.

Development of a simulation model that integrates NPS recreation policy, estimated changes in recreational access, behavior, visitation, and impacts to attributes of economic importance will allow us to test these hypotheses under different experimental flow and GCD operational management scenarios.

Brown Trout Incentivized Harvest

- The average Lees Ferry angler responds to a harvest incentive by increasing trips, effort, and brown trout (*Salmo trutta*) retention.
- An increasing incentive increases the average Lees Ferry angler's willingness to accept to remove a brown trout.

Testing the second hypothesis, using stated preference methods, will allow us to estimate a supply curve for brown trout harvest. This allows for important comparison between stated and revealed preference results (first hypothesis). In addition, an estimate of the supply curve for brown trout harvest would provide inference on how the incentive could be structured to meet future removal targets.

Tribal Resources Research

- Adaptive management provides a unique opportunity, through double-loop-learning, to better include diverse benefits knowledge in formal decision-making processes.

To test this hypothesis, we will use a cultural benefit learning framework (Hoelting and others, 2023) to identify opportunities for improved integration of benefits knowledge, within deliberative, double-loop learning (Williams and Brown, 2018). This process will integrate values and understandings of ethics and well-being that may have been missed in previous problem definition or goal and objective-setting exercises within the GCDAMP.

Background

Project Element J.1. Integrated Models for Adaptive Management

Project Element J.1 will build on the integrated modeling of rainbow trout (*Oncorhynchus mykiss*) and humpback chub (*Gila cypha*) population dynamics, evaluating cost-effective invasive species management alternatives that meet humpback chub viability goals (Bair and others, 2018; Donovan and others, 2019), and the assessment of the economic costs of experimental flows such as trout management and smallmouth bass (*Micropterus dolomieu*) flows (U.S. Geological Survey, 2024). Continued development of integrated models will provide opportunities to assess the value of information gained from monitoring and research within the GCDAMP.

This element will address the humpback chub and nonnative invasive species goals in the Long-Term Experimental and Management Plan Record of Decision (LTEMP ROD) (U.S. Department of the Interior, 2016), along with compliance activities, by improving our understanding of the dynamics between fisheries resources and impacts of management actions.

These modeling methods reduce uncertainty important to and specify triggers that inform proposed management actions in the LTEMP ROD and other proposed management actions.

Sub-element: Integrated Models for Adaptive Management

The integrated modeling element will focus on integrated modeling of native and invasive fishes in Glen and Grand Canyon, leveraging ongoing bioeconomic modeling of the system (Bair and others, 2018; Donovan and others, 2019; U.S. Geological Survey Grand Canyon Monitoring and Research Center, 2024). The project element will emphasize the development of guidance for data collection efforts within the complex bioeconomic system with a continued focus on environmental flow research and hydropower operations at GCD, invasive species monitoring efforts, management for viable endangered species populations, and other socio-economic stakeholder objectives. This systematic approach for the prioritization of program activities is needed to improve the efficiency of how monitoring and research funding is allocated. This 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 prioritize monitoring and research by identifying the relative efficiency of learning opportunities, while also acquiring information on effectiveness and efficiency of management actions.

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 and rainbow trout removals at the Little Colorado River. Continued predictive modeling of multiple resource goals is important as conditions in the Colorado River change, and identifying the relative importance of reducing uncertainties, through application of predictive models, could significantly improve opportunity for cost-effective management. For example, focused effort on one dimension of uncertainty reduction, such as invasive species monitoring and management, is at the expense of efforts allocated toward other management actions, such as monitoring and research related to experimental dam releases for ecosystem restoration. This work aims to clarify the value of each of these actions and the tradeoffs between them while reducing uncertainty about ecosystem health and function. These efforts also support the analysis expected of short-term rapid response in the Invasive Species Strategic Plan (Smallmouth Bass Ad Hoc Group, 2023), evaluating cost of time and resources dedicated to plan implementation and the costs of management actions into the future.

While we intend to utilize existing predictive models of biological and hydropower resources to evaluate the usefulness of monitoring and research, this project element will also undertake a structured value of information (VoI) analysis with a sub-set of downstream resources.

Limiting the initial VoI assessment to a sub-set of high priority resource goals will provide a tractable first step in the development of a model to demonstrate methods and results to the GCDAMP. In the end, adaptive management is an information problem (Doremus, 2011). Its goal is to improve management through reducing uncertainty in our understanding of the structure of environmental systems. Some uncertainties we can't reduce, and the benefits of reducing other uncertainties do not outweigh the costs of experimental management actions. It's the remaining uncertainties that are worth learning more about. Using VoI analysis to characterize uncertainty and identify which uncertainties are worth paying attention to is a way to prioritize monitoring and research when funding is limited (Bolam and others, 2019). We propose the application of VoI analysis in the GCDAMP to assist in the prioritization of monitoring and research. This type of analysis is an important step in adaptive management, where assessing the value of learning is a necessary component for the effective and efficient management of resource goals (Doremus, 2011; Runge and others, 2011).

Project Element J.2. Recreation Monitoring and Research

Project Element J.2 will develop predictive modeling capability for assessment of recreational experience and regional recreational spending under different future management scenarios, as recommended by the GCMRC Socioeconomic Research Review Panel (Hamilton and others, 2010). This research will build on simulation models of recreational activities (Roberts and others, 2002; Gaston and others, 2015; U.S. Geological Survey, 2024) and the estimation of recreational preferences for flows by anglers in Glen Canyon and whitewater rafters in Grand Canyon (Bair and others, 2016; Neher and others, 2017). This project element will also continue to support the NPS in the design and evaluation of the Glen Canyon National Recreation Area brown trout incentivized harvest (IH) program.

Sub-element: Recreation Modeling

The Grand Canyon Protection Act (GCPA) of 1992 states that, "long-term monitoring of GCD 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)). This research element addresses the language in the GCPA and the "Recreational Experience" resource goal in the LTEMP ROD, by undertaking monitoring and research to inform management. Ongoing research has established the importance of flow attributes to recreational users in Glen and Grand Canyons (Bair and others, 2016; Duffield and others, 2016; Neher and others, 2017; 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, there has been no effort to incorporate these research findings into a dynamic model of recreational use and experience in Glen and Grand Canyons, as recommended by a GCMRC Economics Pannel (Hamilton and others, 2010).

This research effort will integrate past research in recreation trip simulation in the Grand Canyon (Roberts and others, 2002) with the estimates of economic parameters developed in revealed and stated preference research (Bishop and others, 1987; Bair and others, 2016; Duffield and others, 2016; Neher and others, 2018). This approach provides the ability to assess recreational experience, including the ability to calculate recreational experience as impacted by proposed management actions in the LTEMP ROD and under different future hydrology. Developing a recreational experience model also allows for the assessment of various aspects of trip behavior that are important to the management of other resources in Glen and Grand Canyons, such as archeological resources, and the regional assessment of recreational spending. Development of the recreational trip model will require collaboration with NPS and AGFD to manage existing, and design and implement the collection of additional, recreation data important to the management of recreational resources. These efforts will focus on the design of best practices for collaborative data collection including prioritizing the collection of data to inform management.

Sub-element: Brown Trout Incentivized Harvest

Harvest incentives are an increasingly popular but understudied price-based tool for invasive species management. Incentivized harvest programs augment recreational hunters' and fishers' pre-existing incentives to hunt and fish by providing a cash reward (i.e., a bounty) for harvesting from a target species. Harvest incentives belong to a broader family of price-based tools designed to subsidize "green" behaviors (Allcott and others, 2015; Sheldon and Dua, 2019). Therefore, IH programs suffer from a similar policy challenge to other green subsidies: uncertainty surrounding "additionality", or the quantity of environmentally beneficial behavior induced by the program (Weitzman, 1974). Programs with low additionality are often cost-inefficient, as they mostly reward green behaviors that would have occurred absent the incentive. Therefore, researchers evaluating green subsidy programs have long recognized the importance of measuring success against a counterfactual (Bennear and others, 2013; Breslford and Abbott, 2021).

This project sub-element will support the NPS in the continued design, implementation, and monitoring of the impacts of an IH program to reduce brown trout abundance in Lees Ferry. The limited research on aquatic IH programs means that how and to what degree Lees Ferry anglers respond to harvest incentives is uncertain (Best, 2006). While there is a significant amount of learning that occurred in the first three years of the program, effective and efficient management of the program requires improved understanding of angler response to monetary incentives, social norms, and the amount and type of educational information available to anglers. This element's objective is to reduce uncertainty surrounding program design by continued monitoring and research of the harvest incentive under a range of conditions over the next year of the program, and final year of research. Reducing uncertainty in angler response to harvest incentives will ultimately improve the NPS's ability to cost-effectively manage invasive fishes in the Colorado River ecosystem.

Project Element J.3. Tribal Resources Research

Project Element J.3 focuses on developing more explicit pathways for recognition and meaningful consideration in the GCDAMP of the values and importance of Tribal resources, and the effects of management on these values. The “Tribal resources” goal in the LTEMP EIS has not been adequately defined, and comprehensive research and monitoring efforts have not yet been designed to inform the GCDAMP on this goal. This project element is envisioned to address a central issue that will support and enable equitable, accurate research and monitoring around the values of Tribal resources: building understanding within the GCDAMP of diverse forms of knowledge that convey plural values linked to ecosystems and resources, and piloting an ecosystem services-based approach to identify and integrate available Tribal benefits knowledge.

The work combines insights from ecosystem services (ES) theory with place-based, context-specific Tribal understandings of well-being, ecosystems, and human-nature relationships. Specifically, we consider how the Cultural Benefits Learning Framework (CBLF) developed by Hoelting and others (2023) can intersect with Tribal research frameworks to increase recognition and integration of diverse knowledge forms that effectively convey the importance of Tribal resources. We intend to evaluate the application of the CBLF framework within the GCDAMP, in collaboration with interested Tribal partners and ongoing Tribal monitoring programs. This process includes close collaboration with Tribal stakeholders in the evaluation of ongoing monitoring programs, translation of monitoring results into decision relevant knowledge products, and the integration of these knowledge products into broader aspects of the decision process within the GCDAMP. Identifying decision-relevant benefits knowledge, and the knowledge forms that can effectively convey that knowledge, will assist in integration of this information into decision-making in the GCDAMP.

Although there is a growing agreement around the need to elevate diverse knowledges in decision-making, there is less clarity in how to achieve this in practice. The CBLF framework helps operationalize knowledge pluralism by directing attention to diverse forms in which benefits knowledge can be made available, and diverse pathways through which learning from this knowledge can occur in environmental decision-making. For example, the meaningful integration of plural values linked to Tribal resources will require recognition that these values are often best conveyed through knowledge practices, and cannot be fully conveyed through quantitative information or written documentation (Hoelting and others, 2024c). The framework is envisioned as a systematic approach to make explicit the diversity of knowledge forms as well as integration pathways most likely to enable learning from these knowledge forms.

Past applications of the CBLF have emphasized improving consideration of plural values associated with cultural benefits specifically. Cultural benefits of ES remain an important focus of this project element, particularly in the second task on “Retrospective analysis and current assessment of Tribal cultural-benefits-knowledge in the GCDAMP.”

This is because of the close association between cultural benefits and value aspects commonly marginalized in ecosystem valuation, e.g., relational values and holistic value perspectives (Hoelting and others, 2024c). However, the theory underlying the CBLF is widely applicable to improving consideration of plural values and value perspectives associated with all ecosystem services and benefits that may be relevant to Tribal resources.

This project task seeks to establish theoretical foundations for research and monitoring of Tribal resources to inform the GCDAMP, grounded in concepts of value pluralism and knowledge pluralism (Hoelting and others, 2024a). This foundation is necessary to ensure pathways are available for integration of plural values – including relational values and holistic value perspectives – alongside the instrumental values typically emphasized in ecosystem valuation and management trade-off analyses (Chan and others, 2018; Himes and Muraca, 2018; Hoelting and others, 2024a). This emphasis attends to recognitional justice needs by working to creating space in decision-making for plural values and the associated diversity of knowledge systems and understandings of well-being (Martin and others, 2016; Gould and others, 2020; Hoelting and others, 2024a). This approach is critical for equitable and accurate research and monitoring around Tribal resources specifically but is also relevant to the GCDAMP broadly; lessons learned through this project element will be relevant to consider for monitoring and evaluating success across multiple GCDAMP LTEMP goals.

This effort will be carried out in collaboration and co-production with Tribal led monitoring activities to ground the conversation in Tribal research frameworks. The theoretical foundations developed in this project task are not intended to replace existing Tribal research frameworks, but rather to support and intersect with them to ensure available forms of Tribal cultural-benefits-knowledge, i.e., those forms of knowledge which Tribes choose to offer, are explicitly recognized and legitimized as valid, decision-relevant knowledge to inform the GCDAMP through varied learning pathways. This work will be carried out in collaboration with Tribal stakeholders involved in the GCDAMP. For additional detail about multiple knowledge systems see Hoelting and others (2024a).

There is a broad need for tools and guidance to support knowledge pluralism in applied environmental management (Hoelting and Gould, 2022; Hoelting and others, 2023), and in U.S. Federal decision-making in particular (e.g., White House, 2021, 2022). In addition to the need for adequate theoretical foundations (see first task of Project Element J.3), there is also a need for decision-support tools and guidance to support implementation and iterative learning. The research proposed in this project task aims to pilot and refine a tool both for natural resource management agency personnel and research scientists, as well as Tribal stakeholders, to identify and engage opportunities for more meaningful consideration of plural values linked to Tribal resources. Specifically, this project task will apply the CBLF outlined by Hoelting and others (2023) to carry out both a) retrospective analysis to understand how Tribal cultural-benefits-knowledge has been made available to the GCDAMP historically, and b) current assessment of available knowledge forms and pathways for their integration.

First, *retrospective* analysis of past GCDAMP decision processes can highlight tangible examples as an avenue for reflection around successes and failures, which in turn can feed into guidance to inform current decision processes. In turn, assessment of *current* decision processes can enable systematic identification of available Tribal cultural-benefits-knowledge-forms and opportunities for their meaningful consideration in on-going decision-making processes. In addition, assessment of current decision-making offers added benefit as a context for social learning among current actors in the GCDAMP, in terms of supporting reflection, systems thinking, negotiation, participation, and integration of diverse knowledges.

Application of the CBLF, as a decision-support tool, can be understood as to offer nested learning opportunities: First, the act of applying the framework offers a social learning process with potential to enhance decision-makers' recognition of the multiple knowledge systems linked to the Grand Canyon ecosystem. Second, the output of CBLF framework application is a list of available forms of benefits knowledge linked to specific opportunities for learning from each knowledge form. These nested outcomes of the CBLF approach can ultimately support diverse learning pathways for meaningful consideration of plural values linked to Tribal resources.

These learning pathways exist across phases of decision-making, including technical and deliberative phases (Brest and Krieger, 2010; Hoelting and others, 2023). Learning opportunities may include a) technical, single-loop learning to refine understanding of ecosystem function and how management actions affect resources and resource values, b) deliberative, double-loop learning to integrate values and understandings of ethics and well-being that may have been missed in previous problem definition or goal and objective-setting exercises, and/or c) triple-loop learning around ways that the existing institutional structures, processes, and paradigms may limit meaningful consideration of particular values or understandings of well-being, i.e., limit consideration of diverse benefits knowledges (Argyris 1977; Pahl-Wostl, 2009; Hoelting and others, 2023, 2024b).

In applying the CBLF to retrospective analysis and current decision assessment of the GCDAMP, this project does not intend to resolve fundamental conflict over natural resource management. Instead, the goal of this tool is to ensure that all forms of cultural-benefits-knowledge relevant to the management of GCD are recognized (Martin and others, 2016; Gould and others, 2020), and identify opportunities, including existing barriers and enabling factors that could be addressed or harnessed, to improve integration of diverse cultural-benefits-knowledge-forms in the GCDAMP (Hoelting and others, 2024b, 2024c).

Proposed Work

Integrated Models for Adaptive Management

This project element will implement interrelated but distinct approaches to further development of dynamic optimization models to improve on predictive modeling of the Colorado River ecosystem and undertake formal VoI analysis.

This first approach provides bioeconomic modeling support for the Glen Canyon Adaptive Management Program. The scope of the project involves directing targeted learning efforts within a complicated ecological system encompassing environmental flow research and hydropower operations at Glen Canyon Dam, invasive species monitoring efforts, management for endangered species for ongoing population viability, and other socio-economic stakeholder objectives in the Colorado River ecosystem. A systematic approach for the prioritization of future fieldwork activities that improve our understanding of this system is of particular importance as conditions in the Colorado River change. We recommend assigning priority based on a value of information (VoI) analysis to improve the efficiency of deployed resources.

This project determines the uncertainties which are most important to reduce within the context of our specific management challenge. The proposed model is an extension of current salmonid and humpback chub models (Bair and others, 2018; Donovan and others, 2019) and addresses learning about the expansion dynamics of smallmouth bass while also managing for viable populations of humpback chub. Learning will center around opportunities for reducing uncertainty in system dynamics during smallmouth bass removals and monitoring while also operating GCD for viable humpback chub populations, river temperature management, and foregone hydropower generation. But explicitly modeling all of these additional model features comes at a high computational cost. The decision model currently applied to the system of interest forces a highly simplified representation of Colorado River ecology in favor of computational feasibility and thus cannot facilitate additional complexity.

To address this computational issue and facilitate our VoI analysis, we will use cutting edge dynamic programming methods (Powell 2011; Springborn and Faig, 2019). The Approximate Dynamic Programming (ADP) innovation allows us to optimize systems multiple orders of magnitude more complicated than previously allowed and provides a way to respond to a more accurate representation of the Colorado River ecosystem. This avoids burdensome assumptions about simplified dynamics that only act as a proxy for the underlying system of interest. ADP also facilitates latent model features that are not directly observed, which is a critical development for cases in which it is infeasible to observe every aspect of a system with 100% certainty. With this modeling paradigm, we can therefore determine the implications of observational focus on one subset of the system versus another.

The second approach to further develop formal decision-making methods within the GCDAMP by implementing a VoI analysis to guide monitoring and research funding decisions. The use of VoI in conservation settings is at an early stage (Bolam and others, 2019). Applying VoI analysis to a multiple-objective adaptive management program provides an opportunity to advance methods used to identify the value of reducing uncertainty, which may be dependent on the program goals and the relative value of resources states.

We will follow steps in VoI analysis outlined in the literature (Runge and others, 2011; Bolam and others, 2019; Healy and others, *in review*).

The first step in the analysis will be to document the GCDAMP's objectives and related performance metrics when managing resources downstream from GCD. We will draw on the existing literature specific to the GCDAMP to accomplish this (Runge and others, 2015; U.S Department of the Interior, 2016). We will focus on a sub-set of resource objectives to implement this initial research project. The resources will be selected based on program priorities as defined by legal requirements, priority based on the set of experimental actions, and share of research funding. A second step will be to identify the complete set of monitoring and research actions that could be used to better meet resource objectives. For each monitoring and research effort, we will consider the observational and structural uncertainty being reduced through monitoring and research. We will then use underlying hypotheses about how the system works, the relative importance, or value, assigned to resources, and the predicted outcomes associated with each monitoring, research, and experimental action to undertake a formal VoI analysis. This approach builds on innovative work by Healy and others (*in review*) and will provide a foundation on which decisions related to monitoring and research funding can be based.

Recreation Monitoring and Research

Recreation Modeling

This project element will develop a simulation model of annual recreational angling in Glen Canyon and whitewater rafting in Grand Canyon using a sub-daily model. The sub-daily model will be based on forecast hydrology, operational constraints at GCD, energy generation and recreational use as determined by NPS policy and forecast visitor use.

The influence of hourly releases at GCD has a significant impact on downstream resources, including river recreation (Bair and others, 2016, Neher and others, 2017). Hourly releases are a function of load following at GCD, where water is released to correspond to electricity demand in the Southwest United States. Demand varies by time of day and season of year, therefore modeling the hourly discharge from GCD over longer time horizons is an important component of evaluating resource outcomes under different scenarios, including low water releases. Therefore, we will integrate a sub-daily energy generation model of flows with recreational use (U.S. Geological Survey Grand Canyon Monitoring and Research Center, 2024).

Recent research has demonstrated that preferences for recreational attributes (water levels) have remained stable over the last 30 years (Bishop and others, 1987; Neher and others, 2017). However, potential scenarios that deviate from historical conditions present significant uncertainty in recreational access and quality. We plan to further develop existing modeling frameworks (Gaston and others, 2015; U.S. Geological Survey, 2024) to estimate how Colorado River flow alteration will impact recreation access, behavior, and quality over a wide range of conditions. Specifically, we aim to address how climate-change related modifications to dam operations, along with general trends in visitation and recreational activity, will influence water-based recreation outcomes.

To address the uncertainty in recreational access and behavior under varying river flow conditions we will update the Roberts and others (2002) model that details decision making during recreational trips. The model will simulate recreational angling and rafting behavior and decision making of individual trips as they seek to optimize their experience. We will utilize federal, state, and private visitation data, recreational management plans, and qualitative information to update existing models of river recreational use and behavior. For example, this includes incorporating the learning that has occurred when modeling recreational response to low flow events and implementation of the brown trout IH program. The updated models will incorporate the latest visitation trends, updated modeling parameters, and quantitative information about access and visitation in operational scenarios outside of historical norms.

The result of this project sub-element will be an individual trip-based model that uses historic recreational data with expected changes in recreational access and behavior under various conditions, incorporating the revealed and stated preference research that has occurred since 2016 (Bair and others, 2016; Neher and others, 2017, 2018). The objective of the model is to better predict and report on recreational experience under a variety of operational scenarios and potential impacts to other downstream resources.

Brown Trout Incentivized Harvest

This project sub-element will finalize research that evaluates four years of the IH program utilizing both revealed and stated preference models. We will perform the first counterfactual program evaluation of an IH program. To do this, we will estimate how the harvest incentive affected three behavioral margins that multiplicatively comprise harvest (trips per day, catch per trip, and retention rate) then use those models to estimate total additional harvest over the four years of the program. Estimating margin-specific regressions should be more accurate than directly estimating the program's effect on total harvest and allow us to identify which margins are or are not being activated by the program.

The dependent variables for our trip, catch, and retention models come from the Arizona Game and Fish Department's (AGFD) creel survey. The Lees Ferry creel is a uniquely consistent and long-running repeated cross section of recreational angling behavior.

We will also build a panel of controls for variables that may impact fishing behavior separate from the program. This panel includes daily data air temperature, precipitation, water temperature, and flow rate. We also include calendar controls (year, weekend, holiday, etc.), and variables meant to capture the effects of COVID-19 on recreational fishing behaviors. Finally, we will include lagged (by one and two months) and unlagged monthly search frequency data from Google Trends for four search terms relevant to the Lees Ferry fishery.

We use these three models to simulate daily estimates for trips taken, average catch per trip, and average retention rates under both "no treatment" and "treatment" scenarios for four years of the Lees Ferry program.

- We will estimate a difference-in-differences (DID) regression of how logged daily trips changed in response to the harvest incentive.
- We will estimate a Poisson DID of how brown trout catch per trip was affected by the IH program.
- We will estimate a pre-post fractional logit of how brown trout retention rates responded to the IH program.

In addition to the revealed preference model, we will use a stated preference survey, to investigate anglers' willingness to accept a harvest incentive payment to retain invasive brown trout in what has traditionally been a catch-and-release fishery. Our stated preference survey will be the first, to our knowledge, to empirically assess why different "types" of recreational harvester might be willing to participate in an IH program. Specifically, we will use the stated preference data to investigate how a recreational fisher's level of specialization, harvest ethic (i.e., whether they tend to catch-and-release or retain their catch), and beliefs about (non-)wild and (non-)native species management affect their price elasticity of supplying population control for invasive brown trout.

We know from an initial analysis of program data from the first two years and from focus groups with Lees Ferry anglers that certain anglers (e.g., those who release any fish they catch or those who fly fish) are less likely to participate in the program. We hypothesize that this trend may be due to a shared underlying ethic (e.g., "retaining fish is wrong") or belief about how fisheries should be managed. Therefore, in addition to the stated preference survey choice experiment questions, we also ask respondents to rank their avidity or degree of specialization as an angler, reflect on how they believe (non-) wild and (non-) native fish species should be managed, and share their impressions of the program. We will use data from these three sections to identify different "types" of anglers with different degrees of willingness to participate in the program.

We will use the choice experiment data to estimate a conditional logit of trip choice on trip and individual-specific characteristics (ISC). The ISCs will include sociodemographic and angler "type" data and will be included in the regression to help us identify the mechanism(s) driving willingness to participate. We will also estimate a latent class model of trip choice using the same data as the conditional logit to further investigate the relationship between angler "type" and the ability of an IH program to increase trip taking (i.e., extensive margin fishing effort). We will also use the choice experiment data to estimate a censored Poisson that examines the effect of the harvest incentive magnitude on the number of brown trout anglers choose to submit to the program. We plan to estimate a censored Poisson because number of brown trout submitted is a count variable that is censored from above by the number of brown trout caught. We will include the same ISCs in this model as in the trip choice model so that we may investigate the effect of angler "type" on this intensive margin of program participation.

Tribal Resources Research

The proposed research outlines a plan for application of the Cultural Benefits Learning Framework (CBLF) detailed in Hoelting and others (2023). This research aims to better understand opportunities for more meaningful consideration of the plural values linked to Tribal resources in the GCDAMP.

First, the "Theoretical foundations for integration in of plural values linked to Tribal resources in Adaptive Management" project task seeks to establish appropriate and equitable theoretical foundations for research and monitoring of Tribal resources to inform the GCDAMP, grounded in concepts of value pluralism and knowledge pluralism (Hoelting and others, 2024a). This project task will explore areas of overlap between learning to reduce structural uncertainty of resource dynamics downstream of GCD and learning to reduce uncertainty related to ethics, epistemologies, and institutional structure in the GCDAMP. Drawing on ecosystem services theory in concert with Tribal research frameworks, this research explores how reducing uncertainty through learning in adaptive management is a promising mechanism for more meaningful consideration of the plural values associated with Tribal resources. This research will involve the following elements:

- Tribal review of an existing preliminary literature review and needs assessment of adaptive management as a mechanism to reduce uncertainty related to plural values and benefits knowledges in adaptative management.
    - Explore possible declaration of principles or other principles to guide application of this theory in the context of the GCDAMP.
- Conduct up to 10 interviews with individuals involved with the GCDAMP to understand:
    - Details of the GCDAMP decision context, including problem definition, objectives, management alternatives, and processes and protocols for stakeholder engagement and learning,
    - Stakeholders and specifically relevant cultural groups,
    - Knowledge forms through which cultural groups seek to convey cultural-benefits-knowledge (e.g., Hoelting, 2023; Hoelting and others, 2024a, 2024b),
    - Areas of uncertainty, and by extension learning opportunities, with respect to decision making in the GGCDAMP and cultural-benefits-knowledge.
- Collaborate with Tribal stakeholders to finalize the literature review and needs assessment, which is envisioned as documentation of theoretical foundations for integration of plural values linked to Tribal resources in adaptive management, including possible declaration of principles or other guidelines identified as necessary or useful by Tribal collaborators.

Second, the “Pilot and refine a decision-support tool for retrospective analysis and current assessment of Tribal cultural-benefits-knowledge in the GCDAMP” project task seeks to pilot the CBLF framework as a tool to understand past successes and limitations around learning from Tribal cultural-benefits-knowledge (retrospective analysis) as well as to identify current opportunities for learning (current decision assessment). Through this process, the research will also support iterative refinement of the CBLF approach. This research will involve the following elements:

- Retrospective Analysis using the CBLF: retrospective case study of cultural-benefits-knowledge integration in the GCDAMP, and
  - Project investigators will conduct interviews and short field visits with a full spectrum of stakeholders.
  - If Tribal participation across the GCDAMP and funding allows, project investigators will support students in initial community meetings and focus groups to launch their fieldwork, and subsequently students will carry out in-person interviews and participant observation, and on-site archival research.
- Current Decision Assessment using the CBLF: assessment of current opportunities for improved integration of cultural-benefits-knowledge in the existing GCDAMP decision-context.
  - Gather GCDAMP actors for a workshop to carry out current decision assessment of Tribal cultural-benefits-knowledge-forms and learning opportunities using the CBLF. Depending on funding, this workshop could be either 1) virtual workshop with a small group of stakeholders representing diverse cultural-benefits-knowledges linked to the Glen Canyon and Grand Canyon areas, 2) an in-person workshop followed by several virtual workshops, or 3) multiple in-person workshops to provide additional support for social learning processes that unfold over time. The latter would allow more adequate space for
    - Reflexivity and mutual understanding around the diverse cultural-benefits-knowledges of workshop participants (i.e., diverse understandings of well-being and human-nature relationship, and aspects of value linked to Tribal resources),
    - Reflexivity and understanding around the diverse forms of valid knowledge that have potential to convey these cultural-benefits-knowledges (i.e., understanding knowledge as a practice in addition to documentation of knowledge as a product, and understanding of pathways through which knowledge practices can support learning in the GCDAMP); and

        - Collaborative refinement of the CBLF process.
    - As part of current decision assessment, this research will also support continued development of Tribal monitoring programs that have the potential to make cultural-benefits-knowledge available to the GCDAMP in various forms. Workshop(s) will focus in part on supporting understandings of knowledge-as-practice workshops, with potential to gather groups of Tribal members, land managers, and scientists during site visits, ceremonies, or other traditional activities for teaching around plant and mineral collection and other phenomenological, experiential, and social learning as practice. Engagements such as this can allow for better understanding of knowledge practices as valid, decision-relevant forms of cultural-benefits-knowledge, foster development of data collection methods to support learning from these knowledge forms (e.g., participant observation, field notes, surveys, photography, and other activities), and provide insights into data organization, analysis, and review protocols.

As part of current decision assessment, this research will further engage with development and refinement of principles and guidelines for equitable, appropriate engagement with Tribal knowledge forms.

Outcomes and Products

Integrated Models for Adaptive Management

- The development of dynamic programming methods for adaptive management in complex bioeconomic systems provides benefits to natural resource economists, ecologists, and program managers operating within and outside of the Grand Canyon setting. Alongside the dissemination of research on the development of the new modeling approach in an academic journal, this project will publish an open-source software package that allows for application to other large, partially observable systems with little overhead.
- A second scientific article will be published that details methods and result of a VoI analysis related to monitoring and research actions in a multi-objective adaptive management program, intended to assist in prioritizing on monitoring and research funding.

Recreation Monitoring and Research

- Scientific article documenting a simulation model that is used to estimate recreational use, behavior, and economic value. The publication will integrate past individual trip-based simulation models (Roberts and others, 2002; Gaston and others, 2015) with the revealed and stated preference research specific to recreational angling in Glen

Canyon and whitewater rafting in Grand Canyon (Bair and others 2016; Neher and others 2018).

- Scientific article of the reveled preference model of the brown trout IH program.
- A scientific article of the stated preference model of the brown trout IH program.

Tribal Resources Research

- Scientific article on the potential of adaptive management to support identification and implementation of opportunities for improved consideration of Tribal benefits knowledge, using examples from the GCDAMP to illustrate challenges and areas of potential.
  - The completion of the first deliverable will allow for a detailed proposal for Phases 2 and 3 of this research proposal.
- Scientific article presenting a retrospective case analysis of Tribal benefits knowledge in the GCDAMP, with a detailed assessment of what a current decision assessment would entail. For an example of retrospective application of the CBLF to another decision context see the Elwha River dam removal and ecosystem restoration in Hoelting and others (2023).
  - Phase 2 would lead to relationship building to enable Phase 3 of this project proposal.
  - Master's thesis or Ph.D. dissertation focused on the intersections between adaptive management and cultural-benefits-knowledge, using the GCDAMP as a core case study; including the most comprehensive relationship building opportunity to enable Phase 3 of this research agenda.
- Development of guiding principles and ideas for future engagements that could be implemented to carry out current decision assessment.
  - Phase 3 would result in completed current decision assessment, and a scientific article detailing the process of carrying out a current decision assessment.
  - Development of cross-cultural comprehension among stakeholder groups and opportunities identified through the workshops to considered for implementation.

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Budget

Fiscal Year 2025									
Project J Socioeconomic Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
J.1. Integrated models for adaptive management	$108,071	$6,000	$15,000	$0	$37,600	$0	$29,265	**$195,936**	
J.2. Recreation monitoring and research	$58,831	$4,000	$10,000	$0	$47,000	$34,100	$17,287	**$171,218**	
J.3. Tribal resources research (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project J	**$166,902**	**$10,000**	**$25,000**	**$0**	**$84,600**	**$34,100**	**$46,553**	**$367,155**	**$21,058**

Fiscal Year 2026									
Project J Socioeconomic Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
J.1. Integrated models for adaptive management	$158,177	$7,000	$17,500	$0	$0	$0	$41,285	**$223,962**	
J.2. Recreation monitoring and research	$94,424	$5,000	$10,000	$0	$0	$17,800	$24,730	**$151,954**	
J.3. Tribal resources research (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project J	**$252,601**	**$12,000**	**$27,500**	**$0**	**$0**	**$17,800**	**$66,015**	**$375,915**	**$30,953**

Fiscal Year 2027									
Project J Socioeconomic Research	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
J.1. Integrated models for adaptive management	$152,410	$7,500	$20,000	$0	$0	$0	$42,099	**$222,009**	
J.2. Recreation monitoring and research	$117,873	$5,500	$10,000	$0	$0	$0	$31,209	**$164,582**	
J.3. Tribal resources research (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project J	**$270,283**	**$13,000**	**$30,000**	**$0**	**$0**	**$0**	**$73,308**	**$386,591**	**$33,721**

*GCDAMP Special Rate: Rate includes current DOI preferred rate (currently 15%; subject to change) and facilities rate (will vary annually). No USGS bureau overhead is charged (unique to the GCDAMP agreement).

**USGS Contributing Funds: The amount of funds required to cover the subsidy created by the reduced burden rate (i.e., GCDAMP Special Rate). As in previous years, SBSC/GCMRC will request these funds of the USGS cost-share program. These funds are not guaranteed.

Project K: Geospatial Science, Data Management and Technology Project

Investigators

Thomas M. Gushue[1], Erica Byerley,[1] Joseph Thomas[1], TBD-Information Technology Specialist (Data Management)[1], TBD-Data Scientist[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Project Summary and Purpose

A crucial component of any long-term adaptive management program is the proper management and accessibility of its data resources necessary for measuring the status, trends, and experimental results related to the program's objectives. The data collected through the U.S. Geological Survey's (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 informed and timely decisions on dam operations. Proper data management and data accessibility is crucial to protect the significant GCDAMP investment spent over more than two decades in collecting these data. 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 (IoT)" where the reliance of web-based technologies has revolutionized our world. This project continues to advance GCMRC's ability to leverage many of these new technologies for the benefit of the science projects described within this work plan, and the larger adaptive management program. 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 the Interior, 2016a, b).

Science Questions

Project K does not address specific science questions as it is inherently a supportive effort for GCDAMP-funded projects and an important resource for geospatial and data management functions. The purpose of this project is to deliver critical support to science projects funded by GCDAMP by contributing expertise across a wide array of data-centric themes including data processing, data management and documentation, programming and source control, geospatial processing and analysis, and advanced data telemetry applications 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 the 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 the 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 Department of the Interior 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 the 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 the Interior, 2016a, b).
- Project K staff participate in USGS-led initiatives, serve on advisory boards and communities of practice, and work to adhere to data management best practices instituted by USGS and the Department of the Interior (Hutchison and others, 2024).

Background

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 GCMRC's responsibilities for managing data in support of the GCDAMP (U.S.

Department of the Interior, 1995). The concept of data management encompasses many facets including, but not limited to, data preservation, design, development and maintenance of systems and applications designed to store and serve the data, building 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 the Interior, 2016a).

GCMRC has experienced some large shifts in how its data resources have been managed. These shifts have often reflected major organizational changes– both internal and external. Examples of these events include the creation of the Southwest Biological Science Center in 2005 and eventual disbanding of the original Information Technology (IT) 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 address the larger questions efficiently and effectively, such as the 10-year assessment that is called for in the LTEMP ROD (U.S. Department of the 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 (U.S. Department of the Interior, 2014, 2017, 2020). 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 (U.S. Department of the Interior, 2014, 2017, 2020). 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 GCMRC. 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 GCMRC, work performed in this project will continue to lead efforts for adhering to these requirements.

In FY 2017, we became involved with an IoT sensor pilot project to test the feasibility of connecting sensors deployed in the field to the Amazon Web Services (AWS) – USGS Cloud Hosting Solutions (CHS) 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 IoT data from water quality instruments located at the Lees Ferry Gage Station, River Mile 0 and the outflow of the Glen Canyon Dam, River Mile –15.7, and fish Passive Integrated Transponder (PIT) Tag scan data from the Little Colorado River. It is important to add that Project K staff have been successful at applying for and being awarded funding from the USGS CHS team and other USGS entities to offset the costs associated with instituting new or improving upon existing data telemetry systems in Grand Canyon.

Proposed Work

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

Work performed within this element will continue to provide the same GIS services and support that have been consistently provided to GCMRC for three previous triennial work plans.

This project is continually striving to improve upon GCMRC's ability to manage its expanding data resources which includes both large, canyon-wide and high-resolution data along with smaller, more site-specific geospatial data representing different sampling locations for a variety of 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. This work is expected to continue, however, there is also a need to provide more analytical support involving geospatial components than in previous work plans. In fiscal years 2025-27, 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, Python programming, and GIS tool development and support. GIS staff support also involves the oversight and supervision of resource-specific project staff with GIS-related tasks including spatial analysis, 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. Examples of this support is evident in past triennial work plans. One example is the processing and analysis work devoted to the Glen Canyon channel map data set (Kaplinski and others, 2022). Specific tasks performed through GIS staff included processing derived data sets from the 2013 Digital Surface Model to remove vegetation from the surface, thus creating a bare-ground elevation surface to be used in conjunction with field-based topography and bathymetry elevation data to make a composite channel map. In FY 2024, the Python scripts used to create channel mapping datasets were updated for compatibility with ArcGIS Pro and function as custom geoprocessing tools to streamline data analysis. This project element is also responsible for publishing geospatial data sets that support all GCMRC projects, as well as working collaboratively with principal investigators to develop and publish data releases, data series reports and peer-reviewed publications in support of GCDAMP-funded science (Gushue, 2019; Sankey and others, 2024).

While this project element strives to support all projects in all facets of GIS, geospatial analysis and geospatial data processing, the needs of individual projects vary widely between each project and, to a lesser degree, from year to year among projects. This project element attempts to align its support with the work proposed by each project for the next triennial work plan and estimates the anticipated support by drawing from both previous GCMRC work plans and gauging on-going efforts in the current fiscal year. In this way, GIS support provided to projects is meant to have some consistency and continuity from year to year and through each work plan cycle. A cross-reference table is provided that highlights general geospatial support components for resource-specific projects (Figure 1).

Project Supported	Asset / Product	Geospatial analysis	Geospatial data processing	Enterprise GIS	Significance of Support	LTEMP Resource Goals
Project A	Sediment and Water Quality	• GIS expertise provided to project staff for geospatial analysis • Python script programming support, GIS tool development	• GIS expertise for processing geospatial data • Geospatial data documentation support • Python script programming support for data processing	• Publish update geospatial data services used in website • Development of online content of sediment monitoring	• Used by researchers and stakeholders across GCDAMP • Used for evaluating HFEs	7. Sediment
Project B	Long-term sediment storage monitoring	• GIS expertise provided to project staff for geospatial analysis • Python script programming support, GIS tool development for analysis	• GIS expertise for processing geospatial data • Geospatial data documentation support • Python script programming support for data processing	• Relational database management for geospatial data • Publishing geospatial services • Online map / web application development	• Used by researchers and stakeholders across GCDAMP • Used for evaluating HFEs	7. Sediment
Project D	Riparian Vegetation Sampling	• GIS expertise provided to project staff for geospatial analysis • Python script programming support, GIS tool development for analysis • Train staff in GIS	• Random sampling site selection support • Modify applications tasks with R scripts for performing analysis • Link riparian vegetation sampling database to geospatial framework	• Link vegetation sampling data to geospatial framework • Database management • Publishing geospatial services • Online map / web application development	• Used for determining visualizing spatial patterns in long-term trends of terrestrial ecology	11. Riparian Vegetation
Project G	Fish Monitoring	• Maintaining / updating fish monitoring units data sets • Nonnative rapid response data curation and analysis • Geospatial analysis leveraging fish monitoring database	• QA/QC support on fish monitoring data for geospatial characteristics • Inclusion of fish monitoring data into geospatial framework • Field river map books generation and production	• Relational database management for geospatial data • Publishing geospatial services • Online map / web application development	• Used by GCMRC staff and cooperators to put spatial context of fish populations	3. Humpback Chub
Project H	Fish Monitoring	• Maintaining / updating fish monitoring units data sets • Database software installation and updates • Database maintenance	• QA/QC support on fish monitoring data for geospatial characteristics • Inclusion of fish monitoring data into geospatial framework • Field river map books generation and production	• Relational database management for geospatial data • Publishing geospatial services on nonnative captures • Online map / web application development	• Used by GCMRC staff and cooperators to put spatial context of fish populations	9. Rainbow Trout Fishery
Project I	Fish Monitoring	• Maintaining / updating fish monitoring units data sets • Nonnative rapid response data curation and analysis • Database maintenance	• QA/QC support on fish monitoring data for geospatial characteristics • Field river map books generation and production, general field support	• Publishing geospatial services such as nonnative rapid response presence	• Used by GCMRC staff and cooperators to put spatial context of fish populations	3. Humpback Chub 5. Other Native Fishes 10. Nonnative Invasive Species

Figure 1. Table shows geospatial analysis, processing and enterprise support for resource-specific science projects funded by GCDAMP.

Enterprise GIS Administration

This project maintains an enterprise GIS platform that is built upon Environmental Systems Research Institute (ESRI) ArcGIS Portal and Server applications and used for maintaining existing online data resources (ESRI, 2024a). 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 applications that can integrate spatial data with resource-specific monitoring data to provide users greater context on the trends and conditions of the Colorado River ecosystem. During FY 2021-23, a repository of Python scripts was developed to convert and move large batches of data to the on-premise Postgres database, from Postgres to the cloud, and from the cloud to ArcGIS Online. This workflow can significantly improve access to data for stakeholders and the public while reducing the time spent by project staff to work data through this process.

During the FY 2025-27 TWP cycle, we will continue to expand on content that is available through this system and work to improve existing functionality, as well as develop new, web-based analytical tools for interacting with and interpreting GCMRC's data.

This Enterprise GIS consists of an on-premises Postgres database instance that serves as the back-end architecture for storing and serving geospatial data both within the DOI internal network and externally through web-based services.

Online services are published using ESRI's ArcGIS Server web-based application which can then be consumed through a variety of online endpoints. GCMRC staff and DOI cooperators can access the on-premise data resources, while both internal and external clients can connect to the data services managed through ArcGIS Server. Project K also manages an online Geospatial Portal content management system (Figure 1) that packages data services into online maps and web applications.

GCMRC Portal URL link: https://grandcanyon.usgs.gov/portal/home/index.html

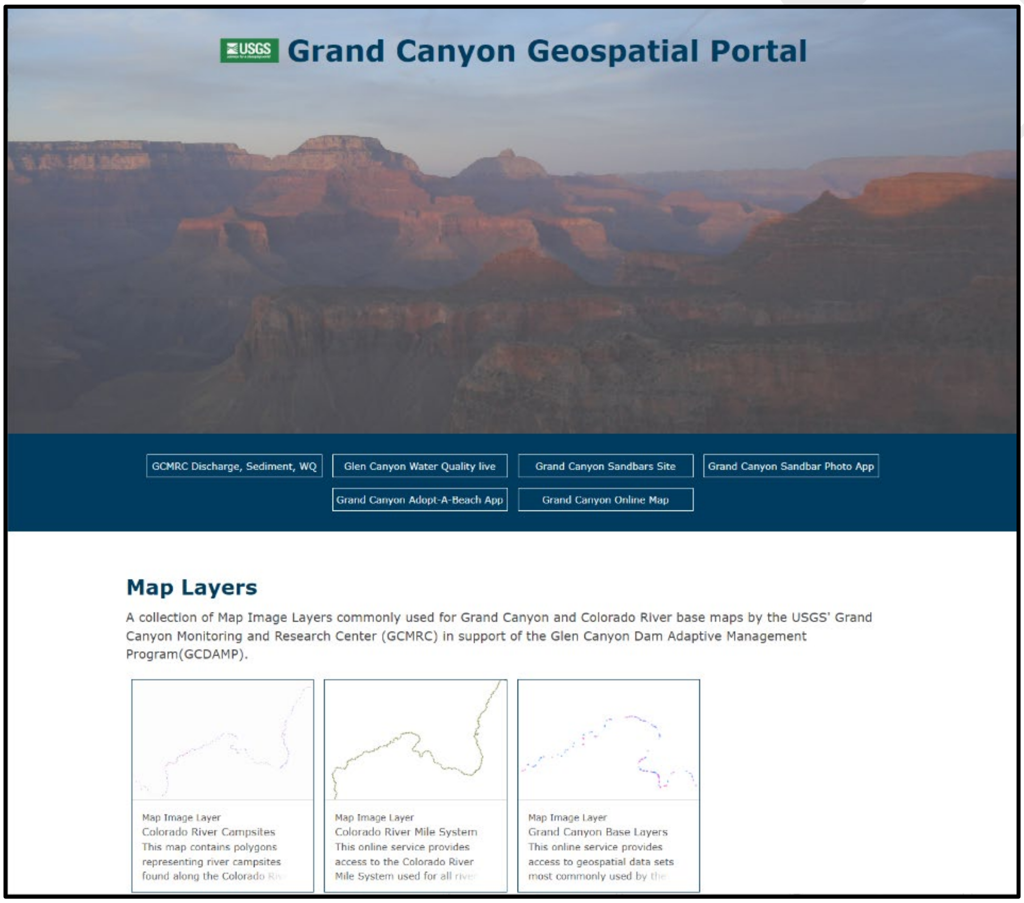

Figure 2. Screen image of GCMRC's Grand Canyon Geospatial Portal that provides access to online geospatial data and contains links to the most used web applications.

Additional GIS Administration tasks related to science support include the testing and migration of computer systems to newer versions of industry-standard GIS/Remote Sensing software, maintaining licensing information, and/or working with IT staff to ensure all licenses, software, extensions, add-ons, and custom applications work properly.

ArcGIS Online

Another aspect of Project K's GIS administration utilizes external cloud-based platforms for sharing GCMRC geospatial data to a wider audience. The best example of this is the extensive list of services hosted on ESRI's ArcGIS Online content management system (ESRI, 2024b). 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 and managed on-premise in a postgreSQL database and served externally through a web server running 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.

URL link to GCMRC GIS on ArcGIS Online:
https://www.arcgis.com/home/search.html?q=GCMRC&t=content&restrict=false

Project Element K.2. Data Management and Database Administration

During the last three years this project has worked towards addressing the need to expand concepts developed in GIS to other data resources across GCMRC. This includes the further development of an integrated spatial and tabular relational database environment for GCMRC. To this end, Project K will continue to 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 is better aligned to provide more comprehensive support to resource-specific science efforts and to the larger GCDAMP community.

Database Administration

Work proposed within this project element includes the continued maintenance of existing relational databases in support of LTEMP related science efforts, and in some cases, the design and development of new databases for projects or resources. Existing, resource-specific databases that have been developed or managed through this project include Sandbar Area and Volume, Riparian Vegetation Survey, Geodetic Network Control, and Lake Powell Water Quality. For the FY 2025-27 TWP, the primary focus will be on the full documentation, redesign, and re-implementation of the existing fish monitoring database. The fish monitoring database is one of the most important data resources maintained by GCMRC, and this project is now better positioned to greatly improve the entire workflow process for storing, reviewing, analyzing, and accessing fish aquatic information. The migration of all project data to relational databases will continue throughout this next triennial work plan. A cross-reference table (Figure 3) is provided that highlights the database and application development components that have been identified as being needed to support resource-specific projects in the next triennial work plan.

Project Supported	Asset / Product	IT / Database Tasks	Application development	Significance of Support	LTEMP Resource Goals
Project A	GCMRC Discharge, Sediment and Water Quality website	• Coordination with Data Center • Server configuration • Database software installation and updates • Database maintenance	• Web application maintenance • Web app development •	• Used by researchers and stakeholders across GCDAMP • Used for evaluating HFEs	7. Sediment
Project B	Sandbar Area and Volume website and application	• Provide some maintenance efforts • Provide updates to online database	• Retain code in source control • Troubleshoot issues / errors • Provide	• Used by researchers and stakeholders across GCDAMP • Used for evaluating HFEs	7. Sediment
Project D	Riparian Vegetation Sampling Database	• Database maintenance • Train / support staff with accessing database	• Maintain data entry application • Modify applications tasks with R scripts for performing analysis	• Used for determining long-term trends in terrestrial ecological and responses to operations	11. Riparian Vegetation
Project G	Fish Monitoring Database	• Server configuration • Database software installation and updates • Database maintenance	• Development of processes for data entry, QA/QC and inclusion into master database	• Used by GCMRC staff and cooperators to estimate fish populations	3. Humpback Chub
Project H	Fish Monitoring Database	• Server configuration • Database software installation and updates • Database maintenance	• Development of processes for data entry, QA/QC and inclusion into master database	• Used by GCMRC staff and cooperators to estimate fish populations	9. Rainbow Trout Fishery
Project I	Fish Monitoring Database	• Server configuration • Database software installation and updates • Database maintenance	• Development of processes for data entry, QA/QC and inclusion into master database	• Used by GCMRC staff and cooperators to estimate fish populations	3. Humpback Chub 5. Other Native Fishes 10. Nonnative Invasive Species

Figure 3. Table showing Grand Canyon Monitoring and Research Center resource-specific projects with relational database support from this project element.

The shift in how we approach our data resources will provide a consistent and stable platform for processing and analyzing much of GCMRC's monitoring and research data within this work plan and beyond. This work will build upon achievements made in database administration since the last triennial work plan. The largest shift since then was the migration away from Oracle and into PostgreSQL, an open-source relational database platform that has provided a fundamental shift in how we manage and access some high-profile data assets. The fish monitoring database is one of those data assets now currently stored in PostgreSQL. We followed an Infrastructure As Code (IaC) process to generate our postgres environment which can allow for faster rebuilds due to system failure and aligns these data resources with a hybrid-cloud strategy that will allow for us to replicate these systems in Amazon Web Services (AWS) or other cloud platforms. In this next triennial work plan, we anticipate that the advance data serving systems developed for geospatial data sets and more recently for the resource-specific data sets, will be better integrated for analysis and informational products. This is illustrated in the GCMRC Enterprise Data System schematic (Figure 4).

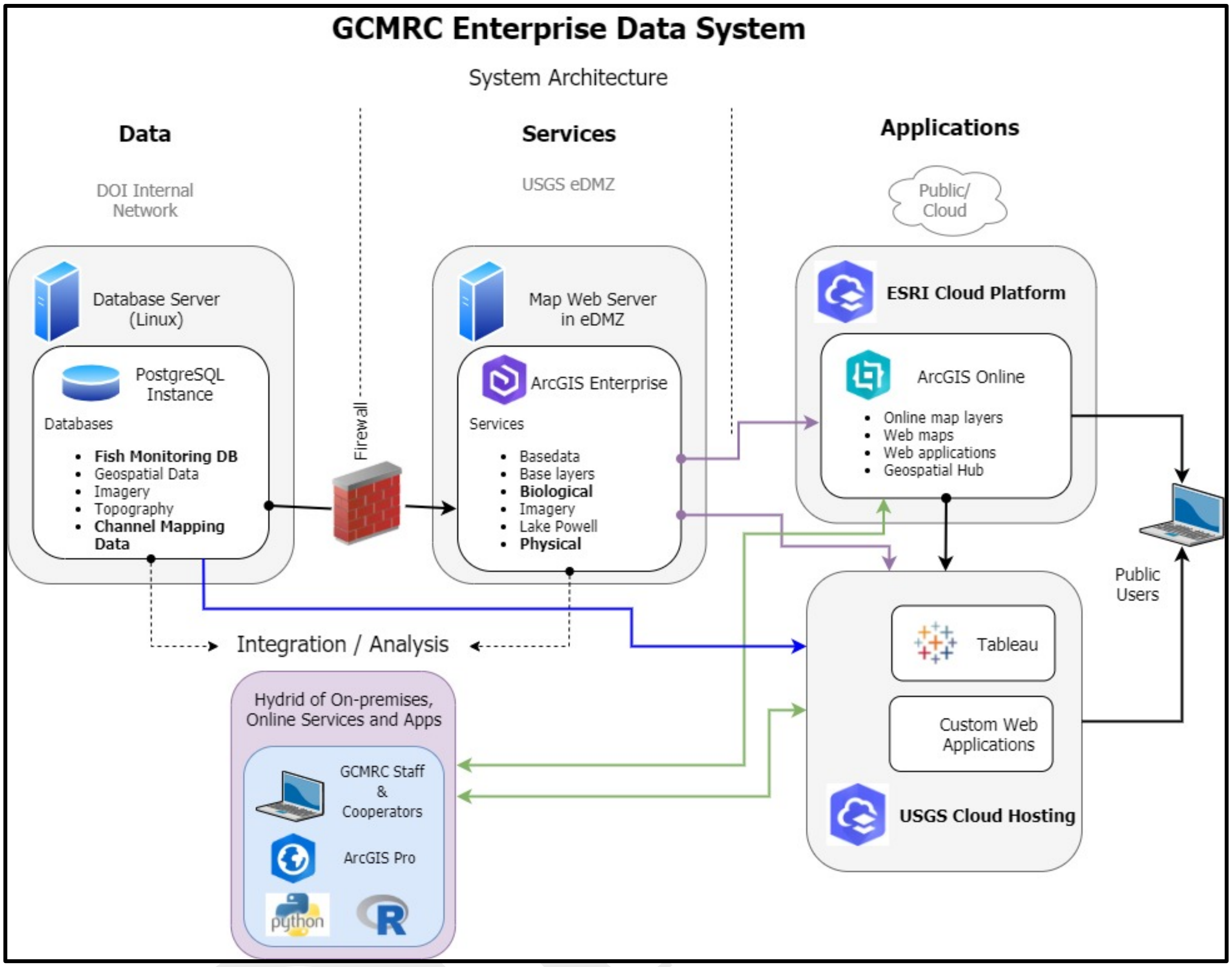

Figure 4. Grand Canyon Monitoring and Research Center enterprise data system architecture schematic, with some example data sets listed within the tiers of this system.

Cloud-based Data Management

Since 2017, this project has led GCMRC's efforts to adopt and use cloud-based environments for providing better access to its data and applications. By working with the USGS Cloud Hosting Solutions (CHS) team, the Project K has continued to lead the way for GCMRC in expanding the use of the 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 for natural resource monitoring 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, as well as continue to investigate other data management solutions being provided through the USGS and the DOI.

Project Element K.3. Data Telemetry and Field Engineering

The natural setting for where GCMRC conducts much of its work involves remote locations throughout Grand Canyon characterized by extreme terrain and harsh environments. This presents challenges in how to monitor important resources at these remote locations. Resource monitoring applications such as remote sensing and data telemetry are a way to leverage newer information technologies to gain better, and more cost-effective, access to monitoring data. While these technologies also have challenges when applied to such remote environments, solutions can and have been developed to greatly reduce the amount of time required for staff to be in the field. Remote monitoring solutions handle these challenges through system design and proper implementation in a way that traditional field site visits cannot. While installing, maintaining, and collecting data from field-based sensors in the Grand Canyon region is difficult, once solutions are applied, those challenges are reduced significantly.

Among the challenges for connecting field-based sensors in this environment are the availability of solar power and adequate connectivity through telecommunications in order to sufficiently supply power to remote monitoring systems and transmit data from these same locations, respectively. Providing power to field sensors in Grand Canyon can be a distinct challenge, especially for field sites located in narrow parts of the canyon. Commercially available equipment for supplying power and telemetry capabilities is very often not designed for these extreme environments, and so GCMRC has had to design, deploy, and maintain custom solutions that provide consistent, reliable access to valuable data for the Colorado River ecosystem (Figure 5).

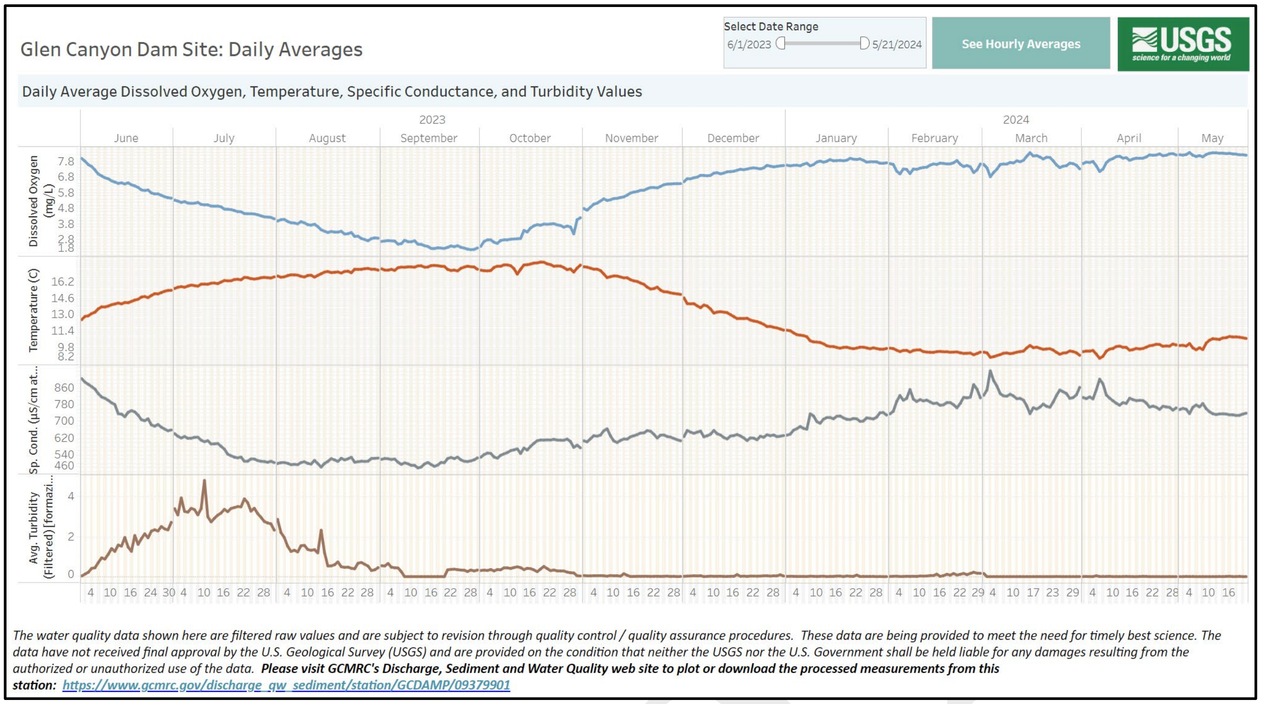

Figure 5. View of online data visualization of Glen Canyon Dam water quality information shared in near real-time, now publicly available with link to quality assessment / quality control version of the data.

Expertise in field engineering and direct current system design, installation and maintenance are required to keep these sites operational. In some instances, these systems have been deployed for more than two decades and underpin some of GCMRC's most critical data collection efforts. Power management, compute, and telemetry systems for sediment gaging sites, fish pit tag antennas, water quality monitoring equipment, and weather stations have all been developed, deployed, and maintained by as part of Project K's field engineering efforts. These systems enable science in Grand Canyon and promote data integrity across the resource-specific projects.

This project element also tracks the technical support and electrical engineering expertise provided to other research projects described in this work plan (Figure 6) which lists specific tasks with individual projects identified, where possible. 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. Some work performed in this element inherently benefits the GCMRC by improving upon the design and development of common components used by most remote monitoring systems deployed by GCMRC.

Project Supported	Engineering Support	Programming Support	Telemetry	Cloud Services	LTEMP Resource Goals	Compliance supported
Project A Sediment monitoring gauges	• Sensor installation /maintenance • Sensor-to-computer telemetry via radio modems • PC power system design / maintenance • Power management system maintenance	• Field computer maintenance and repair • Software development and maintenance	• Starlink dish design, installation, maintenance and repair • Telemetry updates and security maintenance	• Remote access program maintenance • Daily check of site uptime and computer health	7. Sediment	
Project B Sediment storage monitoring	• Power management system maintenance and repair on boats • High-resolution camera (Eyeball) maintenance and repair	• Eyeball interactive software maintenance			7. Sediment	
Project D Monitoring impacts on Arch. sites		• Weather station data collection programming support • Weather station telemetry maintenance and design			1. Archaeological and Cultural Resources	
Project E Controls on ecosystem productivity	• Sensor and telemetry design, installation, maintenance and repair • Maintenance and repair of power system for both field sites • DC power design / 120V AC power design	• Field computer maintenance and repair • Software development and maintenance • Automatic data downloads from sensor	• Cellular modem design, installation, maintenance and repair • Telemetry updates and security maintenance	• Remote access program maintenance • Daily check of site uptime and computer health • Data visualization display via Tableau and email updates	2. Natural Processes	
Project G Humpback chub population dynamics	• Sensor and telemetry design, installation, maintenance and repair • Maintenance and repair of power system both for fish antenna and rim station. • Maintenance and repair of power systems for accessory fish antennas	• Field computer maintenance • Radio antenna maintenance • WiFi bridge maintenance • Software development and maintenance • Automatic data downloads from sensor	• Cellular modem design, installation, maintenance and repair • Telemetry updates and security maintenance	• Remote access program maintenance • Daily check of site uptime and computer health	3. Humpback Chub	
Project H Salmonid research and monitoring	• Sensor and telemetry design, installation, maintenance and repair • Maintenance and repair of power system for both field sites • DC power design / 120V AC power design	• Field computer maintenance and repair • Software development and maintenance • Automatic data downloads from sensor	• Cellular modem design, installation, maintenance and repair • Telemetry updates and security maintenance	• Remote access program maintenance • Daily check of site uptime and computer health • Data visualization display via Tableau and email updates	9. Rainbow Trout fishery	

Figure 6. Table showing Project Element K.3. support to resource-specific projects, the type and level of effort, and the LTEMP resource goals this work supports.

Project K has recently led efforts to develop and install innovative forms of telemetry at multiple sensor locations throughout Grand Canyon. Efforts to enhance field site telemetry are critical for promoting data integrity and reducing field site maintenance costs. Sensor telemetry enables real-time data analysis from sites which previously could only be accessed periodically through site visits. This improved access to sensors allows for rapid identification of data errors or sensor malfunctions, helping to prevent extended data gaps. By having clear information about potential sensor issues as they occur, staff can strategically respond quickly to repair equipment with increased understanding of the maintenance or repair issue prior to visiting the site.

Advances in Low Earth Orbit (LEO) Satellite Communication

In February of 2023 we tested and deployed the first low earth orbit (LEO) satellite telemetry dish in the USGS at the Grand Canyon gaging station near Phantom Ranch, Grand Canyon National Park. Following the success of this effort, LEO telemetry dishes were installed at the 30-mile and 61-mile sediment gaging stations in August 2023. These new systems replaced the legacy geostationary satellite dishes first deployed in 2004, and significantly increasing both data download speed and dependability. Additionally, the LEO data transmission costs have been reduced by one-third from the geostationary service.

Building upon the success of deploying LEO satellite dishes at the long-term sediment monitoring sites (30-mile, 61-mile, Grand Canyon gauge), Project K has continued to pursue the rapidly emerging trends in this realm of data communication. From Fall 2023 through Spring 2024, we have coordinated with SpaceX and the USGS Associate Chief Information Officer (ACIO) to join a SpaceX beta program for testing direct to cell telemetry systems in the remote environments that GCMRC works. Direct to cell telemetry technology is anticipated to be a transformational breakthrough in remote sensor telemetry, fundamentally changing the way that science is conducted in Grand Canyon and opening the possibility of connecting all sensors to the cloud for real-time data transmission and error identification. The objective for continuing this work into FY 2025-27 is to leverage this new telemetry technology to develop and install systems for connecting non-telemetered sensors to the cloud and serve as much data as possible in real-time to scientists and stakeholders.

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Budget

Fiscal Year 2025									
Project K Geospatial Science, Data Management, and Technology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							21.80%		Est Full Rate = 55%
K.1. Enterprise GIS, geospatial analysis, and processing	$160,749	$4,000	$5,600	$0	$0	$0	$37,136	**$207,486**	
K.2. Data management and database administration	$281,300	$1,800	$3,000	$0	$0	$0	$62,370	**$348,470**	
K.3. Data telemetry and field engineering	$140,999	$3,000	$6,550	$0	$0	$0	$32,820	**$183,368**	
Total Project K	**$583,049**	**$8,800**	**$15,150**	**$0**	**$0**	**$0**	**$132,326**	**$739,324**	**$63,309**

Fiscal Year 2026									
Project K Geospatial Science, Data Management, and Technology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							22.60%		Est Full Rate = 55.5%
K.1. Enterprise GIS, geospatial analysis, and processing	$172,002	$4,000	$5,600	$0	$0	$0	$41,042	**$222,644**	
K.2. Data management and database administration	$300,991	$1,800	$3,000	$0	$0	$0	$69,109	**$374,900**	
K.3. Data telemetry and field engineering	$150,869	$3,000	$6,550	$0	$0	$0	$36,255	**$196,673**	
Total Project K	**$623,862**	**$8,800**	**$15,150**	**$0**	**$0**	**$0**	**$146,406**	**$794,218**	**$68,648**

Fiscal Year 2027									
Project K Geospatial Science, Data Management, and Technology	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							23.40%		Est Full Rate = 56%
K.1. Enterprise GIS, geospatial analysis, and processing	$184,042	$4,000	$5,600	$0	$0	$0	$45,312	**$238,954**	
K.2. Data management and database administration	$322,061	$1,800	$3,000	$0	$0	$0	$76,485	**$403,346**	
K.3. Data telemetry and field engineering	$161,430	$3,500	$6,550	$0	$0	$0	$40,126	**$211,606**	
Total Project K	**$667,532**	**$9,300**	**$15,150**	**$0**	**$0**	**$0**	**$161,924**	**$853,906**	**$74,484**

Project L: Overflight Remote Sensing in Support of GCDAMP and LTEMP

Investigators

Joel B. Sankey,[1] Joshua Caster,[1] David Dean,[1] Thomas Gushue

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

Project Summary and Purpose

This project uses remote sensing to monitor the entirety of the terrestrial, riparian, and fluvial ecosystems along the Colorado River from the forebay of Glen Canyon Dam to Lake Mead at Pearce Ferry that are affected by the operation of Glen Canyon Dam. We analyze, interpret, and acquire overflight remote sensing data at a frequency commensurate with significant ecosystem changes along the river, including major tributaries. The imagery and derivative data products from overflight remote sensing are used either directly or indirectly by every science project proposed in each Glen Canyon Dam Adaptive Management Program (GCDAMP) Triennial Work Plan (TWP) to address every resource goal of the Long-Term Experimental and Management (LTEMP; US Department of the Interior, 2016a, b). 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. During FY 2021-24, Project L acquired new remote sensing data from an overflight mission implemented in 2021, and then processed and published those data. The 2021 overflight was the latest in a rich archive of airborne remote sensing in the Grand Canyon in support of the GCDAMP and LTEMP (see https://www.usgs.gov/centers/southwest-biological-science-center/science/airborne-remote-sensing-grand-canyon). Importantly, the 2016 Long-Term Experimental and Management (LTEMP) planning relied heavily on these data and derivative products.

During FY 2025-27, Project Element L.1 of this project will analyze and interpret data from the 2021, and previous, overflights for collaborative science efforts with other projects (A, B, C, D) to address LTEMP resource goals and calculate important LTEMP metrics for assessing sediment and vegetation program objectives. Project Elements L.2 and L.3 of this project will implement the next overflight mission, to acquire imagery and lidar data, respectively. Although significant changes along the Colorado River can happen over days to weeks, we propose limiting data collection to approximately three digital image and topographic datasets per decade in order to maintain a long-term, system-wide, and economically viable remote sensing data record to answer scientific questions about the relationships of dam operations and landcover changes in the Colorado River Ecosystem (CRe) at decadal timescales.

The overflight mission is proposed to occur in FY 2026, to monitor effects of dam operations on the river ecosystem at the 10-year mark – halfway point – of the LTEMP Environmental Impact Statement (EIS) Record of Decision (ROD) implementation (US Department of the Interior, 2016a, b). Note that the science questions outlined in the next section (3., below) are designed to be addressed in Project Element L.1 using overflight remote sensing datasets that have already been acquired and published by USGS; answering the questions is not contingent on first completing the next overflight mission (i.e., Project Elements L.2 and L.3 in FY 2026).

Science Questions

Project Element L.1.

Science Questions

- How have the system-wide area and volume of high elevation sand (sand above the stage of 25,000 ft^3/s that is deposited by HFEs; LTEMP Metric 7.3) changed during the past two decades in relation to dam operations, HFE protocol, and LTEMP experiments?
- Do system-wide remote sensing measurements of high elevation sand provide a more comprehensive metric than the annual monitoring of 45 sandbar sites or triennial monitoring of 40 archaeological sites in Projects B and D, respectively? If so,
- How has the total area of riparian vegetation cover (LTEMP Metric 11.1) changed over 480 km of the river from the current decade (2021) relative to preceding decades since the closure of Glen Canyon Dam?
- How has landcover (i.e., bare sand, total vegetation, and the low flow river channel at 8,000 ft^3/s discharge) changed in the Colorado River ecosystem from the current decade relative to preceding decades since the closure of Glen Canyon Dam?
- How are observed landcover changes related to dam operations, other land use and management activities, or climate and other environmental factors in the ecosystem?

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.

Table 1. Summary of primary datasets and examples of derived products from overflight missions used by GCDAMP science projects to achieve LTEMP 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 · Publication maps
· Fish sampling unit system for mainstem Colorado River	· Humpback chub and juvenile monitoring system for Little Colorado River
· Colorado River centerline and river mile system	· Flowlines · Extracted from low-flow water's edge (~8,000 ft^3/s) in overflight imagery · Modelled from overflight topography and water surface elevation data
· Land cover and landform mapping and change detection · water, sand, vegetation land cover · geomorphic basemap	· Vegetation species classification
· Campsite delineation · Campsite atlas	· Topography data · Topographic change detection · Hydrologic flow modeling.

In 2002, 2005, 2009, 2013, and 2021, 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 2026. 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, 2012; Durning and others, 2016; Sankey and others, 2024; Table 1). That proven methodology was most recently used to publish an image mosaic from the 2021 acquisition (Sankey and others, 2024).

Image mosaics from overflight missions have myriad uses that are critical to different aspects of all of the science implemented through the GCDAMP. 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 similarly the base map layer used to produce website content and online GIS maps, such as the GCMRC GIS Base Map Viewer (Table 1). Many science projects develop detailed study designs in a GIS with the imagery. Examples of such study designs include the fish sampling unit system for the mainstem Colorado River, and the 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).

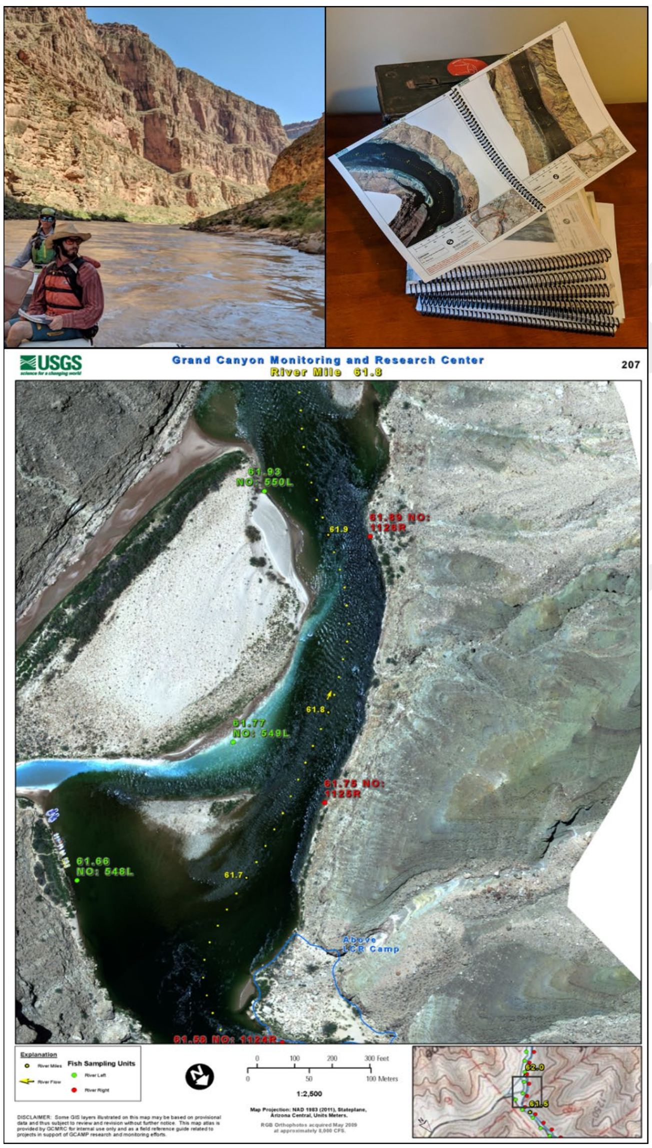

Figure 1. Remote sensing imagery are the base map layer for all map books used by science projects to navigate the river and implement field monitoring and research campaigns. Top left photo shows a scientist consulting his map book on the river. Top right photo shows a stack of map books printed for a recent field campaign. Bottom panel shows a page of a map book with Fish Sampling Units delineated for a recent monitoring campaign.

As with preceding overflight image mosaics, the 2021 overflight image mosaic was published as a USGS data release (Sankey and others, 2024), and GCMRC is now implementing their workflow for producing landcover classification maps derived from that mosaic. The workflow progresses by first publishing USGS data releases of the most basic, fundamental maps of landcover (Figure 2) including:

1) The low-flow river channel at 8,000 ft^3/s (e.g., for the 2013 and preceding overflight image mosaics see landcover classification maps of water: Durning and others, 2017a; Sankey and others, 2015b),
2) Sand and other river sediment (e.g., for the 2013 and preceding overflight image mosaics see river sand classification maps: Sankey and others, 2018c), and
3) Total riparian vegetation (e.g., for the 2013 and preceding overflight image mosaics see landcover classification maps of riparian vegetation: Durning and others, 2017b; Sankey and others, 2015a).

Figure 2. Example landcover classifications of the low-flow river channel at 8,000 ft^3/s (water classification); total riparian vegetation (vegetation classification), and sand and other river sediment deposits (sand classification). For each overflight image dataset, GCMRC publishes USGS data releases of these most basic, fundamental maps of landcover covering the entire river corridor from Glen Canyon Dam to Lake Mead at Pearce Ferry. Various GCMRC projects leverage the landcover classifications, with imagery and topographic data for science that relates observations of environmental change in the Colorado River ecosystem to dam operations, other land use and management activities, climate, and other factors.

GCMRC plans to produce and publish the water channel classification map from the 2021 image mosaic during FY 2024 and will produce and publish the 2021 image mosaic sand and riparian vegetation classification maps during FY 2025. Once those landcover maps are published as USGS data releases, GCMRC remote sensing staff will produce more detailed classification maps, such as maps of riparian vegetation differentiated by species (Bedford and others, 2018a; Durning and others, 2018). Remote sensing staff then collaborate 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). Other examples 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 and others (2021). Hadley and others (2018) used the landcover classifications derived from the imagery to quantify changes in campsites along the river. Sankey and others (2018a, b; 2023) used overflight imagery and topography to assess effects of dam operations on 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. 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.

Durning and others (2021) used the image time series and derived classification maps from 2002-2009-2013 to quantify hydrologic and geomorphic effects on riparian plant species occurrence and encroachment along 360 km of the river corridor in Grand Canyon. Kasprak and others (2017a, b) and Caster and others (2024) used overflight remote sensing digital topographic data and landcover classifications of bare sand and total vegetation to monitor land surface change and its mechanisms at archaeological sites and dunefields. Kasprak and others (2018, 2021) 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. The work of Kasprak and others (2018, 2021) is currently being implemented to model resource impacts for the LTEMP SEIS (Yackulic and others, 2024).

Proposed Work

Project Element L.1. Analysis and Interpretation of Overflight Remote Sensing Data (modified ongoing study)

During FY 2025-27 GCMRC will produce and publish CRe landcover classification maps derived from analysis of the recently published the orthomosaic of high-resolution multispectral imagery acquired during the 2021 overflight (Sankey and others, 2024). GCMRC will conduct change detection analysis of the digital imagery, topography, and landcover datasets derived from the 2021 and prior overflights. This work will support the three major interdisciplinary science efforts outlined in the timeline in Table 2.

Table 2. Timeline of major activities and work effort for Project Element L.1. Analysis and interpretation of overflight remote sensing data during the FY 2025-27 TWP.

Fiscal Year	Project Element L.1 Science Activities

2025	• Produce CRe landcover classification maps derived from analysis of the orthomosaic of high-resolution multispectral imagery (image data release: Sankey and others, 2024).
	  ○ 8,000 CFS low-flow river channel
	  ○ total riparian vegetation cover
	  ○ sand and other river sediment

2026	• Complete change detection analysis of total riparian vegetation cover from 2021 and previous overflight classification maps for the entire 480 km of river from Glen Canyon Dam to Lake Mead at Pearce Ferry. ○ Calculate and report on *LTEMP Metric 11.1 Total Area of Riparian Vegetation Cover* • Prepare digital topographic (DSM) datasets from 2002-2009-2013-2021 overflights for change detection analysis of area and volume of high elevation sand (sand at stage elevations > 25,000 CFS deposited by HFEs) for the entire 480 km of river from Glen Canyon Dam to Lake Mead at Pearce Ferry.

2027	• Conduct DSM change detection analysis and interpret results.
	  ○ Calculate and report on *LTEMP Metric 7.3 High Elevation Sand > 25,000 CFS stage that is deposited by HFEs.*
	  ○ Publish report on high elevation sand change detection study

The first science effort will be to produce landcover change observations for calibration and validation of flow, vegetation, and sediment modeling in support of Projects A, B, C, and D. Each of those projects include interdisciplinary efforts to better quantify how interactions between river sediment, riparian vegetation, and the flow of water or wind affect long-term changes in the Colorado River channel in response to dam operations. Those efforts require landcover classification maps (Figure 2), and change detection analysis of the maps, derived from overflight remote sensing to either calibrate or validate predictive efforts based on other data acquired by those projects. Project Element L.1 will provide the necessary mapping and change detection analysis for those efforts. Classification and change detection methods are detailed in Sankey and others (2015, 2018c), Durning and others (2021), Bedford and others (2018b), and Bransky and others (2021) and employ machine learning, supervised classification, and unsupervised classification remote sensing image analysis methods.

The second science effort will be to analyze overflight imagery to determine *LTEMP Goal 2, Metric 1.1 Total Vegetation Cover.* This LTEMP metric is determined periodically after each aerial image acquisition by mapping all of the riparian vegetation in the CRe, and thus provides a census of total vegetation cover throughout the river corridor. At present, the metric has been calculated from aerial image analysis from 1965 to 2013. See Figure 6 in Sankey and others (2015) and Figure 1 in Durning and others (2021) for examples of the metric spanning 1965-2009 and 1965-2013, respectively. The classification map of total vegetation area will be produced from the 2021 overflight imagery during the first year of this work plan (FY 2025). That classification map of total vegetation within the river channel and riparian area will be interpreted as a function of hydrologic zones based on frequency of inundation: 8,000–25,000 ft^3/s (hydrologic zone 1; areas inundated by powerplant operations of GCD; e.g., hydro-peaking), 25,000–45,000 ft^3/s (hydrologic zone 2; areas inundated by HFEs) and 45,000 ft^3/ and above (hydrologic zone 3; areas not inundated since emergency spillway releases in 1983-84). Methods are detailed in Magirl and others (2008), Sankey and others (2015), and Durning and others (2021). Total vegetation will be summarized by hydrologic zones to calculate and report *LTEMP Goal 2, Metric 1.1 Total Vegetation Cover*.

The third major science effort will be to measure system-wide changes in high-elevation sand deposits using the archive of remote sensing digital topography (termed Digital Surface Models; DSMs) acquired by GCMRC and the GCDAMP from remote sensing overflight missions spanning 2002-2009-2013-2021. The volume of high elevation sand (that is, the sand above the stage of 25,000 ft^3/s) is a combination of sand deposited by pre-dam floods, sand deposited by HFE's, and river sand transported by wind from lower elevations and deposited at higher elevations. In the absence of HFE's, high-elevation sand can be eroded or deposited by wind, eroded by rainfall-driven runoff from canyon walls and hillslopes, or stabilized by vegetation. However, it is primarily through HFE's that any substantial high-elevation sand may be deposited by the Colorado River. Project B measures the volume of high-elevation sand annually at 45 long-term sandbar monitoring sites.

However, it is unknown whether these 45 discrete sandbar sites are diagnostic of system-wide conditions along the 480 km river corridor from Glen Canyon Dam to Lake Mead at Pearce Ferry. Project D measures the volume of high-elevation sand, including sand at even higher elevations than measured in Project B, during ground-based light detection and ranging (lidar) surveys repeated approximately every three years at sandbars and dunefields associated with approximately 40 archaeological sites. However, it is similarly unknown whether those sites are diagnostic of system-wide conditions. Thus, we propose to analyze system-wide DSMs constructed from photogrammetry of overflight imagery in 2021, 2013, 2009, and 2002 to evaluate high-elevation sand conditions within the CRe between Lees Ferry and Diamond Creek. Interpretation of results will be completed in collaboration with Projects B and D to determine if system-wide high-elevation sand conditions agree with or diverge from high-elevation sand conditions at the discrete long-term sandbar or dunefield monitoring sites. This would provide needed information on LTEMP Sediment Resource Goals, determine whether additional sites need to be monitored to sufficiently track high-elevation sand volumes, and assess whether system-wide overflight remote sensing derived high-elevation sand measurements provide a more comprehensive understanding of sand resources throughout the CRe. Methods for performing geomorphic change detection of the DSMs to determine changes in sand storage are detailed in Kasprak and others (2017a), Caster and others (2024), and Sankey and others (2018b) for example sites at Lees Ferry, Soap Creek (Figure 3), and Fossil Canyon.

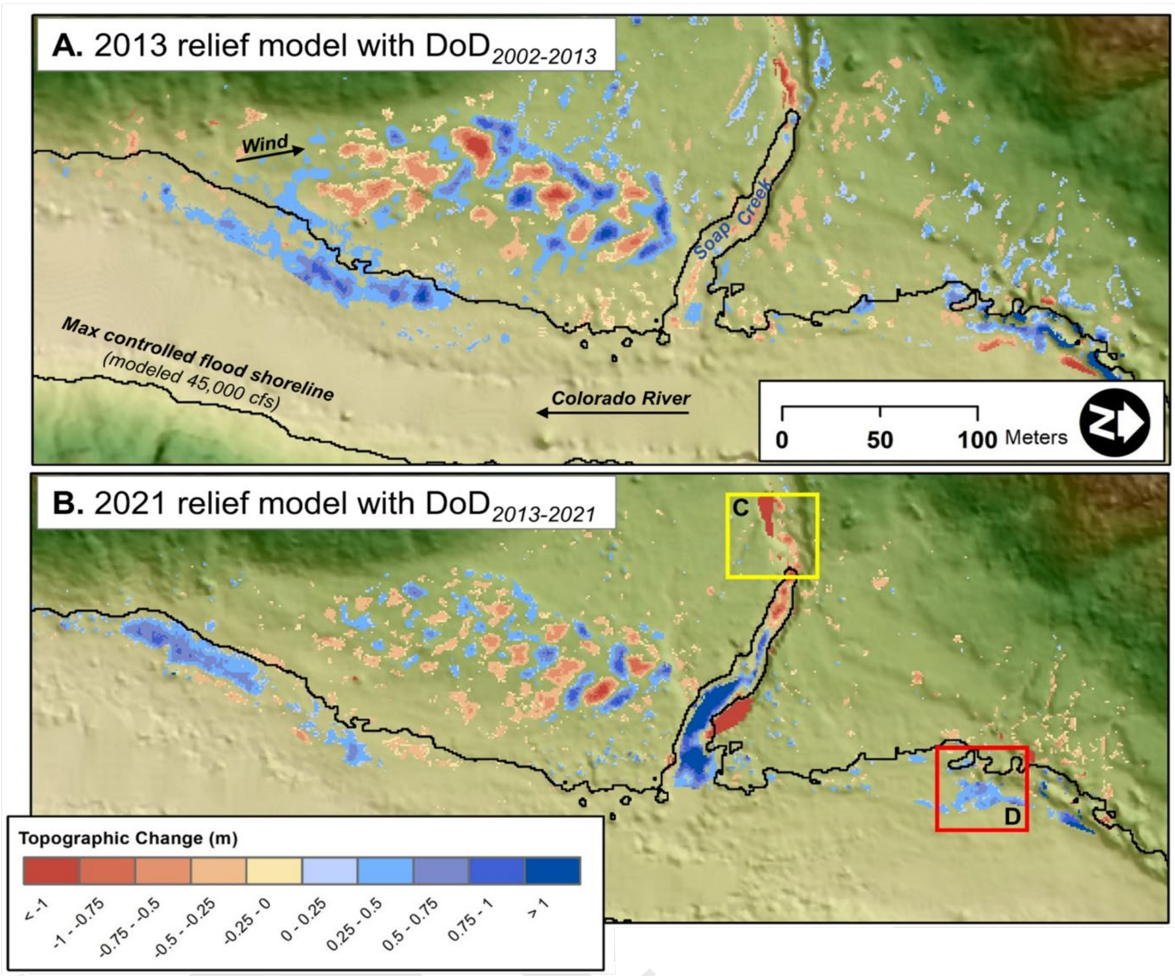

Figure 3. (A) Basemap is a hillshade of the Digital Surface Model (DSM; relief model) acquired from photogrammetry of 2013 overflight imagery. The basemap is overlayed with a colored map of topographic changes the occurred between 2002 and 2013 at the Soap Creek camp site, tributary channel, debris fan, dunefield, and sandbar along the Colorado River in Grand Canyon. Topographic changes were determined by differencing the 2013 DSM and 2002 DSM to produce a DSM of Difference ($DOD_{2002-2013}$). (B) Basemap is a hillshade of the Digital Surface Model (DSM; relief model) acquired from photogrammetry of 2021 overflight imagery. The basemap is overlayed with a colored map of topographic changes the occurred between 2013 and 2021 ($DOD_{2013-2021}$).

Project Element L.2. Acquisition of Overflight Remote Sensing Imagery (new)

During FY 2026, GCMRC will implement a remote sensing overflight to collect high-resolution digital, multispectral imagery and topography of the CRe between Glen Canyon Dam and Lake Mead. To maintain consistency with previously collected digital, orthorectified aerial imagery acquired in 2002, 2009, 2013, 2021 (Davis, 2012; Durning and others, 2016; Sankey and others, 2024), the mission will be conducted during the same time of year (beginning on Memorial Day weekend in the month of May, and lasting for potentially one week or longer depending on weather) and adhere to the same data collection parameters and significant logistical requirements as used in preceding missions.

Specifications for the data acquisition necessitate that dam releases be held at a steady discharge of 8,000 ft^3/s (CFS) for the duration of the overflight mission. As such, the proposed 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, and for image matching and change detection analysis with previous overflight datasets.

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-100 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 a Scope of Work (SOW) contract to be written by GCMRC scientists during FY 2025. The overflight mission would occur in FY 2026. Imagery will be acquired using the manned aircraft overflight and Leica sensor, as opposed to other satellite-based platforms and sensors, for example, in order to produce a seamless orthomosaic that is cloud and shadow free, synoptically covers the entire CRe during the low steady dam release of 8,000 CFS beginning on the anniversary date of Memorial Day weekend and meets the image spatial and spectral resolution requirements stated above.

Project Element L.3. Acquisition of Airborne Lidar in Conjunction with Overflight Remote Sensing Imagery (new)

During the overflight proposed in Project Element L.2, GCMRC proposes to also acquire Quality Level 1 (QLI) or higher resolution airborne lidar data of the CRe. Lidar is a technology that uses a pulsed laser to measure ranges (variable distances) to the Earth. Combined with other data, this generates precise, three-dimensional information about the shape of the Earth's surface and its characteristics. GCMRC will work through the contracting process for these data to be acquired by the same contractor and in parallel with the high-resolution multispectral imagery (L.2).

GCMRC will partner with the USGS 3D Elevation Program (3DEP; https://www.usgs.gov/3d-elevation-program) which is leading an ongoing effort to acquire QL1 airborne lidar data coverage of the entire nation. A large segment of the CRe has yet to be covered by 3DEP. Moreover, 3DEP data acquisition in Grand Canyon to date has not leveraged the low, steady 8,000 CFS flows of the GCDAMP overflight missions. Acquiring these lidar data during the next GCDAMP overflight would ensure that a low steady dam release of 8,000 CFS is maintained during the data collection, which is critical to maximize the potential for monitoring CRe resources with the data (i.e., when they are subaerially exposed and visible, as opposed to underwater in the river channel).

QL1 airborne lidar have a much higher spatial accuracy (latitude, longitude, and elevation) than digital topographic data derived from other airborne remote sensing methods, and thus would be extremely valuable for baseline observations and future monitoring of a variety of resources and applications in the CRe.

Outcomes and Products

Project Element L.1.

- (FY 2025) produce and publish, as USGS data releases, classification maps of the (1) low-flow river channel, (2) riparian vegetation, and (3) river sand, spanning the entire 480 km of the river corridor from Glen Canyon Dam to Lake Mead at Pearce Ferry.
- (FY 2026) use the derived classification maps as well as the primary imagery from the entire archive of remote sensing overflight missions to evaluate the LTEMP metric for total riparian vegetation cover, and to support investigations by other projects in this work plan. The LTEMP metric results will be reported in the GCDAMP annual reporting format.
- (FY 2027) use the derived classification maps as well as the primary topography data from the archive of remote sensing overflight missions spanning 2002-2009-2013-2021 to evaluate the LTEMP metric for high elevation sand. The LTEMP metric for high elevation sand will be reported in the GCDAMP annual reporting format. Analysis and results of the high elevation sand investigation will be published in a USGS report or journal article.

Project Element L.2.

- Oversee the contracting, coordinate with all relevant parties, and oversee the mission to acquire multispectral imagery for the river corridor during a low steady dam release of 8,000 CFS beginning at the start of the Memorial Day holiday weekend. Preliminary image mosaic is delivered by the contractor to GCMRC approximately six months after the mission, and staff then perform QA/QC working with the contractor to iteratively review and request further changes as necessary.

Project Element L.3.

- Oversee the contracting, coordinate with all relevant parties, and oversee the mission to acquire QL1 lidar for the river corridor in conjunction with the acquisition of multispectral imagery during a low steady dam release of 8,000 CFS beginning at the start of the Memorial Day holiday weekend. Preliminary data is delivered by the contractor to GCMRC at a to be determined timeline following the mission, and staff then perform QA/QC working with the contractor to iteratively review and request further changes as necessary.

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Budget

Fiscal Year 2025									
Project L Overflight Remote Sensing in Support of GCDAMP and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							21.80%		Est Full Rate = 55%
L.1. Analysis and interpretation of overflight remote sensing data	$231,481	$9,000	$5,000	$0	$97,596	$0	$56,443	**$399,519**	
L.2. Acquisition of overflight remote sensing imagery (*FY26 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
L.3. Acquisition of airborne lidar in conjunction with overflight remote sensing imagery (*FY26 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project L	**$231,481**	**$9,000**	**$5,000**	**$0**	**$97,596**	**$0**	**$56,443**	**$399,519**	**$25,603**

Fiscal Year 2026									
Project L Overflight Remote Sensing in Support of GCDAMP and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
L.1. Analysis and interpretation of overflight remote sensing data	$254,472	$12,000	$5,000	$0	$100,453	$0	$64,366	**$436,291**	
L.2. Acquisition of overflight remote sensing imagery (*FY26 project only; unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
L.3. Acquisition of airborne lidar in conjunction with overflight remote sensing imagery (*FY26 project only; unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project L	**$254,472**	**$12,000**	**$5,000**	**$0**	**$100,453**	**$0**	**$64,366**	**$436,291**	**$28,767**

Fiscal Year 2027									
Project L Overflight Remote Sensing in Support of GCDAMP and LTEMP	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
L.1. Analysis and interpretation of overflight remote sensing data	$272,285	$12,000	$5,000	$0	$103,396	$0	$70,795	**$463,476**	
L.2. Acquisition of overflight remote sensing imagery (*FY26 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
L.3. Acquisition of airborne lidar in conjunction with overflight remote sensing imagery (*FY26 project only*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project L	**$272,285**	**$12,000**	**$5,000**	**$0**	**$103,396**	**$0**	**$70,795**	**$463,476**	**$31,138**

Project M: Leadership, Management, and Support

Investigators

Andrew A. Schultz[1], Gregory "Mark" Anderson[1], Meredith A. Hartwell[1], Renata E. Macy[1], Ann-Marie D. Bringhurst[1], Camile D. Diab[1], Logistics support staff[1]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center

Project Summary

Project M includes salaries, travel, and operating expenses for the management and operation of GCMRC. For USGS information product release and program administration, M.1 includes partial salaries for the following support staff: Budget Analyst (81%), Public Affairs Specialist (50%), Information Product Data System/Archive Technician (50%), and a Science Data Coordinator (50%). Leadership and management personnel salaries include those for the GCMRC Chief and Deputy Chief. Half of the salary for one Principal Investigator for tribal coordination and LTEMP Metrics development and reporting is currently proposed as unfunded (funding anticipated from other pathway[s]). Project Element M.1 also covers GCMRC travel and training costs ($16,000 annually), including PI travel to support AMWG and TWG meetings. GCMRC operating expenses include GSA vehicle costs (e.g., monthly lease fees, mileage costs, and costs for accidents and damage; $70,000 annually) and DOI vehicle costs (e.g., fuel, maintenance, supplies, and replacement costs; $45,000 annually). An annual contribution ($25,000) to the GCMRC equipment and vehicles working capital fund is currently proposed as unfunded.

Project Element M.2 covers salaries for four members of the GCMRC logistics staff (one member was transferred from Project I to logistics in FY 2024 to meet workload demand). The GCMRC logistics section facilitates all field efforts of the GCMRC and many cooperator agencies. Cooperator funding for support of the Partners in Science Program with Grand Canyon Youth is currently proposed as unfunded (FY 2025 = $40,341; FY 2026 = $40,551; FY 2027 = $42,798).

Project Element M.3 covers GCMRC's information technology equipment and related support costs (FY 2025 = $59,510; FY 2026 = $57,250; FY 2027 = $65,750; reduced from previous TWP by ~$82,000 total).

Budget

Fiscal Year 2025									
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							21.80%		Est Full Rate = 55%
M.1. Leadership, management, and support	$710,605	$16,000	$115,000	$0	$0	$0	$183,470	**$1,025,075**	
M.2. Logistics staff	$413,565	$0	$0	$0	$40,341	$0	$91,367	**$545,274**	
M.3. IT	$0	$0	$59,510	$0	$0	$0	$12,973	**$72,483**	
Total Project M	**$1,124,171**	**$16,000**	**$174,510**	**$0**	**$40,341**	**$0**	**$287,811**	**$1,642,833**	**$137,119**

Fiscal Year 2026									
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							22.60%		Est Full Rate = 55.5%
M.1. Leadership, management, and support	$760,348	$16,000	$115,000	$0	$0	$0	$201,445	**$1,092,792**	
M.2. Logistics staff	$442,515	$0	$0	$0	$40,551	$0	$101,225	**$584,291**	
M.3. IT	$0	$0	$57,250	$0	$0	$0	$12,939	**$70,189**	
Total Project M	**$1,202,863**	**$16,000**	**$172,250**	**$0**	**$40,551**	**$0**	**$315,608**	**$1,747,272**	**$147,414**

Fiscal Year 2027									
Project M Leadership, Management, and Support	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							23.40%		Est Full Rate = 56%
M.1. Leadership, management, and support	$813,572	$16,000	$115,000	$0	$0	$0	$221,030	**$1,165,602**	
M.2. Logistics staff	$473,491	$0	$0	$0	$42,798	$0	$112,081	**$628,370**	
M.3. IT	$0	$0	$65,750	$0	$0	$0	$15,386	**$81,136**	
Total Project M	**$1,287,063**	**$16,000**	**$180,750**	**$0**	**$42,798**	**$0**	**$348,496**	**$1,875,107**	**$159,716**

*GCDAMP Special Rate: Rate includes current DOI preferred rate (currently 15%; subject to change) and facilities rate (will vary annually). No USGS bureau overhead is charged (unique to the GCDAMP agreement).

**USGS Contributing Funds: The amount of funds required to cover the subsidy created by the reduced burden rate (i.e., GCDAMP Special Rate). As in previous years, SBSC/GCMRC will request these funds of the USGS cost-share program. These funds are not guaranteed.

Project N: Native Fish Population Dynamics* (New Project)

*Note that Project N was previously **Hydropower Monitoring and Research.** That project is no longer continuing, and instead Project N will be a new project, **Native Fish Population Dynamics**.

Investigators

Brian D. Healy[1], Lindsay E. Hansen[1], Kimberly L. Dibble[1], Maria Dzul[1], Charles B. Yackulic[1], Lucas Bair[1], Bridget Deemer[1], Drew Eppehimer[1], David Ward[2], Pilar Rinker[2], David Rogowski[3], Emily Omana Smith[4], Laura Tennant[4], Martinique Chavez[5], Brandon Albrecht[6], Ron Rogers[6]

[1]U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
[2]U.S. Fish and Wildlife Service
[3]Arizona Game and Fish Department
[4]National Park Service, Grand Canyon National Park
[5]American Southwest Ichthyological Researchers, LLC.
[6]BIO-WEST, Inc.

Project Summary and Purpose

The Long-term Experimental and Management Plan (LTEMP; U.S. Department of the Interior, 2016)) includes a goal for "other native fishes" (ONF), which applies to razorback (*Xyrauchen texanus*), flannelmouth (*Catostomus latipinnis*), and bluehead (*C. discobolus*) suckers and speckled dace (*Rhinichthys osculus*) in the Colorado River Ecosystem (CRe) including Colorado River tributaries: *"Maintain self-sustaining native fish species population and their habitats in their natural ranges in the Colorado River and its tributaries"*. Monitoring of fishes in the CRe has been conducted for >20 years, and yet few analyses of these data have occurred at a system-wide level to understand basic drivers of ONF population dynamics, how LTEMP flow and non-flow management actions have affected ONF, and whether progress toward the LTEMP goal is being achieved. Also, a comprehensive analysis of efficacy of conservation measures in the LTEMP Biological Opinion (U.S. Department of the Interior, 2016) for razorback sucker (*Xyrauchen texanus*) is needed. Dam-related flow and non-flow management actions related to the LTEMP Biological Opinion, including high flow experiments, suppression of nonnative fishes, or macroinvertebrate flows, may influence fish populations in unexpected ways that are both beneficial (Healy and others, 2020; Deemer, 2022; Hansen and others, 2023) and detrimental (Healy and others, 2022) to LTEMP resource goals. Further analyses are needed at the population and community level to understand how ONF demographic rates and LTEMP metrics (e.g., proportion of CRe and tributaries occupied by ONF) may respond to management actions.

Significant changes in the CRe are occurring as Glen Canyon Dam discharge becomes warmer in summer due to declining reservoir levels (Dibble and others, 2021), leading to increased reproduction rates and distribution of native fishes (Kegerries and others, 2020; Gilbert and others, 2022; Dzul and others, 2023), potential declines in cold-water nonnative salmonids (Bruckerhoff and others, 2022; Healy and others, 2023), and increased entrainment and expansion of warm-water nonnative sport fishes from Lake Powell (Eppehimer and others, 2024). While abundance or catch rates of humpback chub (*Gila cypha*) and ONF have increased (Van Haverbeke and others, 2017; Rogowski and others, 2018), the expansion in warm-water nonnative sport fishes may threaten the existing native fish community (Eppehimer and others, 2024). Managers are developing novel flow alternatives to respond to new fish introductions and expansions in the Colorado River (U.S. Department of the Interior, 2024) that may also compel managers to consider fish conservation actions focused on tributaries (Bouska and others, 2023). Tributaries have been important to native fish populations when conditions in the mainstem were less conducive to successful native fish reproduction (Yackulic and others, 2014). Tributaries continue to provide reproduction and potential rearing habitat (Healy and others, 2020; Bonjour and others, 2023) but the relative importance of tributary and mainstem habitats in maintaining ONF populations and meeting LTEMP goals is unclear. Thus, a baseline understanding of system-wide ONF population dynamics is needed to understand drivers of survival, recruitment, and basic ecology to inform management.

Endangered Species Act (ESA)-listed razorback sucker was considered extirpated from the Grand Canyon beginning in the mid-1990s, and despite the presence of adults and evidence of spawning after 2012, the species continues to be rare (Kegerries and others, 2017; Gilbert and others, 2022). Conservation measures in the LTEMP (U.S. Department of the Interior, 2016) are focused on understanding the status and life stage- or habitat-specific vulnerabilities of razorback sucker. Despite documented spawning (Gilbert and others, 2022), no evidence of recruitment from larval to juvenile life stages has been uncovered in the Grand Canyon – it is unclear if the thermal regime, habitat, predation, or other factors limit the razorback sucker in the CRe. Movements of razorback sucker between the Grand Canyon and Lake Mead, where the only population supported by natural reproduction exists (Albrecht and others, 2010; Albrecht and others, 2017), suggests the populations are linked. Adaptive management actions are being considered to both recover razorback sucker in the CRe and Lake Mead and learn about factors limiting their population growth. For example, a three-year pilot-level razorback sucker augmentation project (Healy and others, 2022b) was initiated with the release of passive-integrated transponder (PIT) tagged age-1 razorback sucker in Havasu Creek by the NPS in 2023. Long-distance movements and dispersal of newly released razorback sucker may require a system-wide approach to understanding the fate of both adult and age-1 PIT-tagged fishes (Pennock, McKinstry, and Gido, 2020; Pennock and others, 2024). Glen Canyon Dam Adaptive Management Program (GCDAMP) interagency monitoring programs have and may continue to detect or capture razorback sucker.

Thus, the Grand Canyon presents a unique opportunity to study larval and juvenile survival, growth, and recruitment in a rapidly changing system with fewer existing predators, which are thought to limit natural recruitment and recovery of razorback sucker in other parts of the Colorado River basin (Marsh and Langhorst, 1988; Marsh and Brooks, 1989; Schooley and Marsh, 2007).

Decisions related to fisheries management actions in the CRe are becoming more difficult under uncertain system-wide change and due to the desire to balance a diversity of values held by Traditionally Associated Tribes and stakeholders, alongside management agency mandates. Department of the Interior utilizes predictive models in many decision-making processes for fish management (Runge and others, 2011a; Runge and others, 2018), but adequate models for ONF have not been developed for the CRe and tributaries. In general, predictions of the outcomes of management actions are also plagued by uncertainty (Runge and others, 2011b). Uncertainty may become increasingly important as new stressors and changes in water quality impact the CRe in ways that may be difficult to predict. Nonetheless, in systems facing rapid change or newly expanding nonnative fishes, timely decision-making is particularly relevant despite uncertainty in the outcome of taking a management action. The costs and effort needed to maintain important ecological values are often greater once an invader has become established, for instance (Healy and others, 2023). Managers may wrestle with different sources of uncertainty during decision-making processes, but not all sources of uncertainty in predictions of management outcomes are important. Value of information (VoI) analytical tools can be used to assist managers in understanding the importance of sources of uncertainty to decision-making and quantifying the tradeoffs between making an immediate management decision under uncertainty or waiting to conduct additional research. The development of predictive models based on long-term ONF data, and VoI tools can assist managers and researchers in prioritizing future monitoring to improve the outcomes of LTEMP flow and non-flow management for ONF, while also considering diverse values of GCDAMP stakeholders, agencies, and tribes.

Project N specifically addresses research to understand ONF population dynamics and assess progress toward LTEMP goals for native fishes using a mix of existing data types, and data collected using new technology, to assess management actions. We will incorporate long-term ONF data collected from throughout the CRe by cooperating agencies (also see projects G and I), including GCMRC, Arizona Game and Fish Department (AZGFD), U.S. Fish and Wildlife Service (USFWS), and National Park Service (NPS), and others in tributaries (Little Colorado River, Bright Angel, Shinumo, and Havasu creeks) and the mainstem Colorado River, to estimate demographic rates (recruitment, survival, population growth), and distribution and abundance using mark-recapture and occupancy models. Mark-recapture modeling has proven to be useful for understanding temporal and spatial variation in survival and growth for humpback chub (Yackulic and others, 2014; Healy and others 2022a; Dzul and others, 2023), inferring interspecific interactions between native and nonnative species (Yackulic and others, 2018), and understanding the outcomes and influences of management actions on native fish populations (Yackulic and others, 2021; Healy and others, 2022a; Hansen and others, 2023; Healy and

Omana Smith, 2023). Movement rates and the use of tributary and mainstem habitats by ONF will also be assessed using a mix of acoustic and PIT-tag telemetry methods (e.g., Bonjour and others, 2023; Dzul and others, 2022). We will explore the use of new acoustic tag technology (Mensinger and others, 2024) to understand both movements and predation as a source of mortality to ONF. Results from these modeling efforts will be incorporated into predictive models to assess future management alternatives and support DOI decision-making processes.

The outcome of this project will support the use of monitoring data for key management needs including informing state-dependent decision-making, evaluating the effectiveness of both flow and non-flow management actions with respect to LTEMP goals, and provide a structure for future learning through the identification and prioritization of key uncertainties making decision-making difficult (Lyons and others, 2008). Collaborations between GCRMC, federal and state management agencies, and contract biologists to analyze existing capture, mark-recapture, and PIT tag antenna detection data collected over decades from throughout the CRe and tributaries should allow for unprecedented learning related to the ecology of ONF and improved understanding of influences of LTEMP flow and non-flow management actions. The work proposed in project N is achievable over fiscal years 2025-2027 because most data have already been collected; however, modeling, and other work proposed would provide a baseline for future work plans as more demographic data are collected during monitoring efforts described in projects G, H, and I.

Hypotheses and Science Questions

The science questions proposed in the FY 2025-27 GCDAMP Triennial Work Plan (TWP) are new because project N is a new project. We propose several basic questions we would attempt to answer, if project N is funded, related to native fish population dynamics, and drivers of recruitment, growth, and survival:

1) What are the long-term relationships between variation in temperature, river discharge, and other extrinsic factors in the CRe with recruitment, growth, and survival of native fishes?
2) What are the effects of flow experiments and other management actions (removals or flow management to suppress warm-water and cold-water nonnative fish species) on native fish population dynamics?
3) Which species of warm-water nonnative fish should be prioritized for monitoring and management to minimize negative population-level impacts on native fishes?
4) How much mortality in juvenile native fishes is related to predation?
5) What are growth, survival, and dispersal rates of juvenile razorback sucker and how do they compare to other populations where augmentation programs occur?

Background

Native fishes, including razorback sucker listed under the ESA, and Colorado River endemic bluehead and flannelmouth suckers, have been sampled as through GCDAMP-funded monitoring programs for over 25 years. Yet, few analyses have been undertaken to understand how and if LTEMP goals are being met for "other native fishes" including speckled dace, bluehead, flannelmouth, and razorback suckers. Meeting this goal may become increasingly difficult as expansion of warm-water sport fishes occur. Further, understanding the role of tributary and mainstem habitats is needed to develop and implement future management actions meant to maintain populations of these fishes (Bouska and others, 2023). For example, construction of barriers meant to provide refuge from introduced predators may result in isolation and extirpation rather than metapopulation maintenance (Bouska and others, 2023).

Project N is proposed to be minimally funded in the FY 2025-27 TWP. Thus, limited insight will be gained into the above science questions. Nonetheless, we proposed to fund a graduate student to answer a subset of the above science questions in the next work plan.

Proposed Work

Project Element N.1. Sucker and Dace Distribution and Demographic Modeling

Evaluate Population Distribution and Dynamics using System-wide Capture and Mark-recapture Data

This project element involves 1) using existing data to estimate the probability of occurrence (occupancy) of all ONF to support the evaluation of trends in LTEMP metrics, 2) a synthesis of environmental and mark-recapture data to estimate demographic rates of bluehead and flannelmouth suckers throughout the CRe, and 3) assist NPS and USFWS in estimating growth and survival of razorback sucker released in Grand Canyon as part of a pilot-level augmentation study (2023-2025). Finally, 4) we plan to collaboratively investigate drivers of early life stage dynamics of ONF using larval and small-bodied fish data (2014-present, ASIR, Inc., and BIO-WEST, Inc.) collected in cooperation with the Bureau of Reclamation. All four emphasis areas in this project depend on the availability of sufficient data for each of the ONF species. It is particularly uncertain whether sufficient recaptures of razorback sucker released as part of the augmentation project will allow for estimation of growth and survival rates (Project Element N.3 may also assist managers in understanding the fate of these fish using acoustic telemetry). Nonetheless, the ultimate objective of Project Element N.1 is to understand and relate long-term variation in environmental (e.g., temperature, watery quality, flow regimes) and biological (e.g., predators, competitor abundance) drivers to ONF demographics (recruitment, survival). Because native fishes often use both tributary and mainstem habitats for different life history stages, and tributary occupancy may impart an advantage to native fishes, we intend to incorporate both tributary and mainstem interagency data into these analyses.

By incorporating system-wide capture or detection data (including through PIT-tag antennas), we may begin to also understand the importance of tributaries and mainstem habitats in supporting native fish populations to inform future management actions.

Project Element N.2. Predictive Modeling and Decision Support for Native Fishes

Development of Predictive Models and Value of Information Analysis

For Project Element N.2, we will use the results of demographic modeling in Project Element N.1 to develop predictive models to inform management and decision-making for ONF (e.g., matrix-based models, metapopulation viability model; Runge and others, 2018; Healy and others, 2023). Management decisions may include where and how to focus ONF restoration, augmentation (razorback sucker), or translocation efforts, how to protect native fish populations (e.g., in tributary refuges above barriers), prioritization of uncertain threats including nonnative species, or those related to LTEMP flow actions, among others. GCMRC scientists will work with the U.S. Department of the Interior and state managers, tribes, and GCDAMP stakeholders, as appropriate, to outline decisions to be made related to GCDAMP recommendations for ONF conservation and LTEMP management objectives, facilitate the development of alternatives, and make predictions about the outcomes of different potential management alternatives. We will also identify and prioritize different sources of uncertainty, and the influence of uncertainty on decision-making for ONF using VoI tools such as expected value of perfect information or expected value of partial perfect information. These tools will allow for the prioritization of future research towards critical uncertainties.

Project Element N.3. Evaluating Dispersal and Sources of Mortality of Razorback Sucker using New Technology

Evaluate Dispersal and Predation as a Source of Mortality to Razorback Sucker Released in the Grand Canyon using Acoustic Telemetry with Predation Sensors

Razorback sucker recovery is thought to be plagued by low survival of juvenile or subadult fish due to predation by introduced predators in other Colorado River basin populations. Populations of razorback sucker have not grown in the Grand Canyon despite the presence of adults and seasonally warming water temperatures, with lower nonnative predator loads in much of the western Grand Canyon where most razorback sucker detections have occurred. Further, rapid and long-distance dispersal of razorback suckers or other native fishes from release sites can complicate interpretation of survival of translocated fish or outcomes of stocking (Spurgeon and others, 2015; Franssen and others, 2021). Predation by nonnative fishes, including by catfishes (Ictaluridae), smallmouth bass (*Micropterus dolomieu*), and others, has been identified as a concern in the existing and future CRe. Quantifying predation rates, and how the likelihood of predation varies spatially, may assist managers in recovering ONF by identifying areas where predation is likely to occur.

For Project Element N.3, we propose to use acoustic telemetry to quantify dispersal from release sites and predation as a source of mortality of age-1 razorback sucker released in the CRe. New acoustic tags equipped with predation sensors will be used to assess the probability of predation and location of predation events (e.g., Schultz and others, 2017; Mensinger and others, 2024) following release of razorback sucker, or other fishes, if deemed appropriate. Once consumed by a predator and exposed to stomach acids, predation sensor tags switch emission signals and signify that a predation event has occurred. A network of acoustic receivers will be temporarily (~4-5 month duration) installed near release sites and in other appropriate areas thought to be important for native fishes, to detect movements and predation event signals from acoustic tagged fish. Multistate mark-recapture models will be used to estimate the likelihood of predation across the network (Mensinger and others, 2024). Predation sensor tags are slightly larger than PIT-tags, and the size of fish tagged will be large enough (100-150 mm total length) to avoid predation by humpback chub, but not avoid the gape of most introduced predator sport fishes (e.g., smallmouth bass, trout, walleye [*Sander vitreus*], catfishes). These tags have been tested and used successfully in Atlantic salmon (*Salmo salar*) smolts in rivers of the Northeast United States (Mensinger and others, 2024). We will first review testing results for these tags, identify the type of tag most appropriate for our application, and conduct validation trials as needed (e.g., Schultz and others, 2017).

Outcomes and Products

Project Element N.1 (with currently proposed funding levels)

Outcomes

- A PhD student will analyze existing native fish data to answer a subset of priority science questions listed above (specific questions are to be determined, in consultation with the project lead, graduate student, and PhD committee members).

Products

- If funded, presentations will be given at the Annual Reporting meeting and at regional meetings, and 1-3 peer-reviewed manuscripts will be produced through the course of the student's graduate work. A dissertation will be finalized in the next work plan, assuming a doctoral degree requires at least 4 years to complete.

Project Element N.1 and N.2 (at initially proposed funding levels)

Outcomes

If full funding was provided for N.1 and N.2, based on earlier estimates proposed (i.e., 3-year average of $136k and $45k for N.1 and N.2, respectively, to cover salaries in FY 2025-27):

- Occupancy modeling to calculate LTEMP metrics for ONF.

- Demographic analysis for flannelmouth, bluehead, and razorback suckers, including linking estimates of survival, recruitment, and growth and link to flow experiments and non-flow actions, and other environmental variables.
- Predictive models to support decision-making will be produced, followed by value of information analysis to understand whether uncertainties in drivers of population dynamics matter for decision-making. This information would be used to establish priorities for research in future analysis and work plans (e.g., determine how important future research may be to inform management decisions).

Products

- If funded, presentations will be given at the Annual Reporting meeting and at regional meetings, and 4-5 manuscripts will be produced.

Project Element N.3 (at initially proposed funding levels)

Outcomes

If full funding was provided for N.3, based on earlier estimates proposed (3-year average of $182k cover salaries and operating costs in FY 2025-27):

- Estimates of predation as a source of mortality for released razorback sucker; additional information will provide evidence of where predation may occur (e.g., tributary vs mainstem, Little Colorado inflow reach). Estimates of movement rates of razorback sucker to inform future release strategies for the razorback sucker augmentation program.

Products

- If funded, presentations will be given at the Annual Reporting meeting and at regional meetings, and a minimum of 1 manuscript will be produced.

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Budget

Fiscal Year 2025									
Project N Native Fish Population Dynamics	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
							21.80%		Est Full Rate = 55%
N.1. Sucker and dace distribution and demographics (SADDAD)	$0	$0	$0	$0	$22,217	$0	$667	**$22,884**	
N.2. Predictive modeling and Decision support for native fishes (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
N.3. Evaluating dispersal and sources of mortality (Razorback sucker) using new technology (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project N	**$0**	**$0**	**$0**	**$0**	**$22,217**	**$0**	**$667**	**$22,884**	**$0**

Fiscal Year 2026									
Project N Native Fish Population Dynamics	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							22.60%		Est Full Rate = 55.5%
N.1. Sucker and dace distribution and demographics (SADDAD) (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
N.2. Predictive modeling and Decision support for native fishes (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
N.3. Evaluating dispersal and sources of mortality (Razorback sucker) using new technology (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project N	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

Fiscal Year 2027									
Project N Native Fish Population Dynamics	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**AMP Special Burden Rate***	**Total**	**USGS Contributing Funds****
							23.40%		Est Full Rate = 56%
N.1. Sucker and dace distribution and demographics (SADDAD) (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
N.2. Predictive modeling and Decision support for native fishes (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
N.3. Evaluating dispersal and sources of mortality (Razorback sucker) using new technology (*unfunded at this time*)	$0	$0	$0	$0	$0	$0	$0	**$0**	
Total Project N	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

Total TWP Budget by Year

Total (FY25-27 TWP)	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	AMP Special Burden Rate*	Total	USGS Contributing Funds**
									Est Full Rate = 56%
Total (FY25)	$5,309,563	$118,265	$703,551	$972,466	$1,497,280	$392,520	$1,593,557	**$10,587,202**	**$740,919**
Total (FY26)	$5,915,119	$129,615	$576,906	$1,085,505	$1,448,220	$386,960	$1,785,261	**$11,327,587**	**$816,715**
Total (FY27)	$6,213,369	$127,265	$552,958	$999,145	$1,423,326	$382,600	$1,889,600	**$11,588,263**	**$849,565**
Total (FY25-27)	**$17,438,051**	**$375,145**	**$1,833,415**	**$3,057,116**	**$4,368,826**	**$1,162,080**	**$5,268,418**	**$33,503,052**	**$2,407,198**

Appendix 1. Budget Allocation by Year

FY 2025

				Fiscal Year 2025					
Project	**Project Description**	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
								21.80%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$184,094	$6,000	$6,000	$27,000	$0	$174,800	$48,634	**$446,528**
A.2	Continuous water quality parameters	$116,673	$1,000	$12,000	$26,000	$0	$29,260	$33,937	**$218,869**
A.3	Sediment transport and budgeting	$339,465	$6,000	$48,000	$26,200	$0	$154,360	$91,487	**$665,512**
	Total A	**$640,232**	**$13,000**	**$66,000**	**$79,200**	**$0**	**$358,420**	**$174,058**	**$1,330,910**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar and campsite monitoring with topographic surveys and remote cameras	$228,820	$2,000	$4,000	$27,391	$23,500	$0	$57,867	**$343,578**
B.2	Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$355,170	$2,000	$2,000	$0	$18,800	$0	$78,863	**$456,833**
B.3	Control network and survey support	$0	$0	$0	$0	$0	$0	$0	**$0**
B.4	Streamflow, sediment, and sandbar modeling	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total B	**$583,990**	**$4,000**	**$6,000**	**$27,391**	**$42,300**	**$0**	**$136,730**	**$800,410**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$127,205	$3,615	$3,500	$80,293	$12,542	$0	$47,162	**$274,317**
C.2	Determining hydrological tolerances and management tools for plant species of interest	$13,701	$0	$0	$0	$44,272	$0	$4,315	**$62,289**
C.3	Predictive models and synthesis	$5,016	$0	$0	$0	$40,014	$0	$2,294	**$47,324**
C.4	Biogeomorphic Linkages between streamflow, sediment transport, and vegetation composition	$0	$0	$0	$0	$0	$0	$0	**$0**
C.5	Vegetation management decision support	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total C	**$145,922**	**$3,615**	**$3,500**	**$80,293**	**$96,828**	**$0**	**$53,771**	**$383,929**

D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Monitoring the effects of dam operations on archaeological sites	$121,118	$10,000	$20,000	$34,714	$0	$0	$40,511	**$226,343**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$7,138	$3,000	$2,500	$0	$0	$0	$2,755	**$15,393**
D.3	Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$11,852	$9,000	$2,500	$12,268	$0	$0	$7,765	**$43,385**
D.4	Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen	$0	$0	$0	$0	$0	$0	$0	**$0**
D.5	Monitoring petroglyphs and pictographs with photogrammetry and lidar	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total D	**$140,108**	**$22,000**	**$25,000**	**$46,982**	**$0**	**$0**	**$51,032**	**$285,122**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$64,625	$0	$13,539	$1,225	$0	$0	$17,307	**$96,696**
E.2	Rates and composition of primary producers in the Colorado River	$149,106	$4,000	$63,045	$3,150	$0	$0	$47,808	**$267,109**
E.3	Understanding the energetic basis of the food web in Western Grand Canyon	$61,053	$1,000	$3,408	$0	$0	$0	$14,271	**$79,732**
E.4	Productivity at higher trophic levels	$67,249	$0	$3,000	$0	$0	$0	$15,314	**$85,563**
	Total E	**$342,034**	**$5,000**	**$82,992**	**$4,375**	**$0**	**$0**	**$94,699**	**$529,101**
F	**Aquatic Invertebrate Ecology**								
F.1	Invertebrate and bat monitoring in Marble and Grand Canyons	$255,416	$4,000	$36,000	$0	$0	$0	$64,401	**$359,816**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$173,361	$4,000	$3,000	$875	$0	$0	$39,509	**$220,746**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$23,189	$2,000	$0	$14,436	$45,825	$0	$10,013	**$95,463**
F.4	Invertebrate and fish diet studies	$86,626	$2,000	$1,500	$14,436	$0	$0	$22,795	**$127,357**
	Total F	**$538,592**	**$12,000**	**$40,500**	**$29,747**	**$45,825**	**$0**	**$136,718**	**$803,382**
G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$148,527	$8,000	$12,000	$0	$0	$0	$36,739	**$205,266**
G.2	Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$4,809	$0	$20,222	$102,192	$415,090	$0	$40,187	**$582,500**
G.3	Juvenile chub monitoring near the LCR confluence (JCM-East)	$153,012	$2,000	$31,156	$301,244	$0	$0	$106,256	**$593,668**
G.4	Remote PIT-tag array monitoring in the LCR	$22,557	$0	$5,500	$4,000	$0	$0	$6,988	**$39,046**
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$4,013	$0	$12,436	$79,366	$142,984	$0	$25,177	**$263,976**
G.6	Juvenile chub monitoring - Western Grand Canyon (JCM-West)	$0	$0	$0	$0	$0	$0	$0	**$0**
G.7	Chute Falls translocations	$0	$0	$0	$0	$0	$0	$0	**$0**
G.8	Sampling of springs in the upper LCR	$0	$0	$0	$0	$0	$0	$0	**$0**
G.9	Movement in western Grand Canyon from system-wide antenna monitoring	$10,946	$0	$47,000	$0	$0	$0	$12,632	**$70,578**
	Total G	**$343,864**	**$10,000**	**$128,314**	**$486,802**	**$558,074**	**$0**	**$227,980**	**$1,755,034**
H	**Salmonid Research and Monitoring**								
H.1	Rainbow trout fishery monitoring in Glen Canyon	$7,609	$0	$0	$0	$88,000	$0	$4,299	**$99,908**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$80,450	$2,500	$88,800	$112,771	$0	$0	$62,026	**$346,547**
H.3	Salmonid modeling	$38,163	$0	$6,000	$0	$0	$0	$9,628	**$53,791**
	Total H	**$126,222**	**$2,500**	**$94,800**	**$112,771**	**$88,000**	**$0**	**$75,952**	**$500,245**

I	**Non-native Invasive Species Monitoring and Research**								
I.1	System-wide native fishes and invasive aquatic species monitoring	$8,661	$0	$3,100	$103,855	$217,550	$0	$31,731	**$364,897**
I.2	Estimating kinship and spawner abundance of warm-water non-natives	$67,051	$0	$200	$0	$140,445	$0	$18,874	**$226,570**
I.3	Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$92,592	$2,150	$31,685	$1,050	$63,504	$0	$29,695	**$220,676**
I.4	Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$174,691	$200	$1,800	$0	$0	$0	$38,519	**$215,210**
	Total I	**$342,996**	**$2,350**	**$36,785**	**$104,905**	**$421,499**	**$0**	**$118,819**	**$1,027,354**
J	**Socioeconomic Research**								
J.1	Integrated models for adaptive management	$108,071	$6,000	$15,000	$0	$37,600	$0	$29,265	**$195,936**
J.2	Recreation monitoring and research	$58,831	$4,000	$10,000	$0	$47,000	$34,100	$17,287	**$171,218**
J.3	Tribal resources research	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total J	**$166,902**	**$10,000**	**$25,000**	**$0**	**$84,600**	**$34,100**	**$46,553**	**$367,155**
K	**Geospatial Science, Data Management, and Technology**								
K.1	Enterprise GIS, geospatial analysis, and processing	$160,749	$4,000	$5,600	$0	$0	$0	$37,136	**$207,486**
K.2	Data management and database administration	$281,300	$1,800	$3,000	$0	$0	$0	$62,370	**$348,470**
K.3	Data telemetry and field engineering	$140,999	$3,000	$6,550	$0	$0	$0	$32,820	**$183,368**
	Total K	**$583,049**	**$8,800**	**$15,150**	**$0**	**$0**	**$0**	**$132,326**	**$739,324**
L	**Overflight Remote Sensing in Support of GCDAMP and LTEMP**								
L.1	Analysis and interpretation of overflight remote sensing data	$231,481	$9,000	$5,000	$0	$97,596	$0	$56,443	**$399,519**
L.2	Acquisition of overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
L.3	Acquisition of airborne lidar in conjunction with overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total L	**$231,481**	**$9,000**	**$5,000**	**$0**	**$97,596**	**$0**	**$56,443**	**$399,519**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$710,605	$16,000	$115,000	$0	$0	$0	$183,470	**$1,025,075**
M.2	Logistics staff	$413,565	$0	$0	$0	$40,341	$0	$91,367	**$545,274**
M.3	IT	$0	$0	$59,510	$0	$0	$0	$12,973	**$72,483**
	Total M	**$1,124,171**	**$16,000**	**$174,510**	**$0**	**$40,341**	**$0**	**$287,811**	**$1,642,833**
N	**Native Fish Population Dynamics**								
N.1	Sucker and dace distribution and demographics (SADDAD)	$0	$0	$0	$0	$22,217	$0	$667	**$22,884**
N.2	Predictive modeling and Decision support for native fishes	$0	$0	$0	$0	$0	$0	$0	**$0**
N.3	Evaluating dispersal and sources of mortality (Razorback sucker) using new technology	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total N	**$0**	**$0**	**$0**	**$0**	**$22,217**	**$0**	**$667**	**$22,884**
	Total (FY25)	**$5,309,563**	**$118,265**	**$703,551**	**$972,466**	**$1,497,280**	**$392,520**	**$1,593,557**	**$10,587,202**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$10,000,000**
	AMP Over/Under Budget								**($587,202)**
	Anticipated Carryover Funding Available								$0
	Other Carryover/non-AMP Funding								$0
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								($587,202)
	Lake Powell Water Quality Monitoring								
	Lake Powell water quality monitoring	$177,977	$0	$0	$0	$0	$0	$97,887	**$275,864**
	GCMRC Grand Total (w/ Lake Powell)	**$5,487,540**	**$118,265**	**$703,551**	**$972,466**	**$1,497,280**	**$392,520**	**$1,691,444**	**$10,863,065**

FY 2026

Fiscal Year 2026									
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
								22.60%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$196,981	$6,000	$6,000	$28,000	$0	$180,120	$53,558	**$470,658**
A.2	Continuous water quality parameters	$124,840	$1,000	$12,000	$26,800	$0	$30,080	$37,209	**$231,929**
A.3	Sediment transport and budgeting	$363,227	$6,000	$48,000	$27,000	$0	$158,960	$100,395	**$703,583**
	Total A	**$685,048**	**$13,000**	**$66,000**	**$81,800**	**$0**	**$369,160**	**$191,162**	**$1,406,169**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar and campsite monitoring with topographic surveys and remote cameras	$262,687	$2,000	$4,000	$31,921	$23,500	$0	$68,642	**$392,751**
B.2	Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$415,078	$2,000	$5,000	$86,680	$37,600	$0	$116,107	**$662,465**
B.3	Control network and survey support	$0	$0	$0	$0	$0	$0	$0	**$0**
B.4	Streamflow, sediment, and sandbar modeling	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total B	**$677,764**	**$4,000**	**$9,000**	**$118,601**	**$61,100**	**$0**	**$184,750**	**$1,055,215**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$136,109	$3,615	$3,500	$85,182	$13,327	$0	$52,020	**$293,753**
C.2	Determining hydrological tolerances and management tools for plant species of interest	$15,197	$0	$0	$0	$48,681	$0	$4,895	**$68,773**
C.3	Predictive models and synthesis	$10,735	$0	$0	$0	$48,846	$0	$3,891	**$63,472**
C.4	Biogeomorphic Linkages between streamflow, sediment transport, and vegetation composition	$0	$0	$0	$0	$0	$0	$0	**$0**
C.5	Vegetation management decision support	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total C	**$162,041**	**$3,615**	**$3,500**	**$85,182**	**$110,854**	**$0**	**$60,806**	**$425,998**
D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Monitoring the effects of dam operations on archaeological sites	$192,081	$10,000	$20,000	$35,866	$0	$0	$58,296	**$316,243**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$22,914	$3,000	$1,000	$0	$0	$0	$6,082	**$32,996**
D.3	Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$73,299	$9,000	$2,500	$12,699	$0	$0	$22,035	**$119,533**
D.4	Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen	$0	$0	$0	$0	$0	$0	$0	**$0**
D.5	Monitoring petroglyphs and pictographs with photogrammetry and lidar	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total D	**$288,294**	**$22,000**	**$23,500**	**$48,565**	**$0**	**$0**	**$86,413**	**$468,772**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$53,103	$2,000	$3,500	$700	$0	$0	$13,403	**$72,706**
E.2	Rates and composition of primary producers in the Colorado River	$137,167	$5,250	$47,092	$1,750	$0	$0	$43,225	**$234,483**
E.3	Understanding the energetic basis of the food web in Western Grand Canyon	$30,258	$0	$0	$1,750	$0	$0	$7,234	**$39,242**
E.4	Productivity at higher trophic levels	$72,198	$0	$3,000	$0	$0	$0	$16,995	**$92,193**
	Total E	**$292,727**	**$7,250**	**$53,592**	**$4,200**	**$0**	**$0**	**$80,856**	**$438,624**

F	**Aquatic Invertebrate Ecology**								
F.1	Invertebrate and bat monitoring in Marble and Grand Canyons	$246,606	$4,250	$42,000	$0	$0	$0	$66,185	**$359,041**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$143,275	$3,250	$4,500	$875	$0	$0	$34,329	**$186,229**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$33,325	$2,250	$0	$14,741	$48,175	$0	$12,817	**$111,307**
F.4	Invertebrate and fish diet studies	$101,334	$2,250	$2,000	$14,741	$0	$0	$27,193	**$147,518**
	Total F	**$524,539**	**$12,000**	**$48,500**	**$30,357**	**$48,175**	**$0**	**$140,525**	**$804,095**
G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$201,395	$8,000	$5,000	$0	$0	$0	$48,453	**$262,849**
G.2	Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$3,017	$0	$20,222	$105,220	$421,215	$0	$41,668	**$591,342**
G.3	Juvenile chub monitoring near the LCR confluence (JCM-East)	$157,969	$2,000	$29,656	$314,734	$0	$0	$113,985	**$618,344**
G.4	Remote PIT-tag array monitoring in the LCR	$24,136	$0	$2,000	$2,000	$0	$0	$6,359	**$34,495**
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$3,017	$0	$12,436	$64,639	$145,034	$0	$22,452	**$247,577**
G.6	Juvenile chub monitoring - Western Grand Canyon (JCM-West)	$0	$0	$0	$0	$0	$0	$0	**$0**
G.7	Chute Falls translocations	$0	$0	$0	$0	$0	$0	$0	**$0**
G.8	Sampling of springs in the upper LCR	$0	$0	$0	$0	$0	$0	$0	**$0**
G.9	Movement in western Grand Canyon from system-wide antenna monitoring	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total G	**$389,535**	**$10,000**	**$69,314**	**$486,593**	**$566,248**	**$0**	**$232,917**	**$1,754,607**
H	**Salmonid Research and Monitoring**								
H.1	Rainbow trout fishery monitoring in Glen Canyon	$7,402	$0	$0	$0	$88,000	$0	$4,313	**$99,714**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$81,826	$2,500	$68,800	$115,875	$0	$0	$60,794	**$329,795**
H.3	Salmonid modeling	$71,181	$0	$6,000	$0	$0	$0	$17,443	**$94,624**
	Total H	**$160,408**	**$2,500**	**$74,800**	**$115,875**	**$88,000**	**$0**	**$82,550**	**$524,133**
I	**Non-native Invasive Species Monitoring and Research**								
I.1	System-wide native fishes and invasive aquatic species monitoring	$7,140	$0	$3,100	$110,692	$217,550	$0	$33,857	**$372,339**
I.2	Estimating kinship and spawner abundance of warm-water non-natives	$69,138	$0	$200	$0	$140,445	$0	$19,884	**$229,667**
I.3	Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$125,727	$4,250	$3,700	$3,640	$74,844	$0	$33,279	**$245,440**
I.4	Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$198,962	$2,200	$1,800	$0	$0	$0	$45,869	**$248,831**
	Total I	**$400,967**	**$6,450**	**$8,800**	**$114,332**	**$432,839**	**$0**	**$132,889**	**$1,096,277**
J	**Socioeconomic Research**								
J.1	Integrated models for adaptive management	$158,177	$7,000	$17,500	$0	$0	$0	$41,285	**$223,962**
J.2	Recreation monitoring and research	$94,424	$5,000	$10,000	$0	$0	$17,800	$24,730	**$151,954**
J.3	Tribal resources research	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total J	**$252,601**	**$12,000**	**$27,500**	**$0**	**$0**	**$17,800**	**$66,015**	**$375,915**
K	**Geospatial Science, Data Management, and Technology**								
K.1	Enterprise GIS, geospatial analysis, and processing	$172,002	$4,000	$5,600	$0	$0	$0	$41,042	**$222,644**
K.2	Data management and database administration	$300,991	$1,800	$3,000	$0	$0	$0	$69,109	**$374,900**
K.3	Data telemetry and field engineering	$150,869	$3,000	$6,550	$0	$0	$0	$36,255	**$196,673**
	Total K	**$623,862**	**$8,800**	**$15,150**	**$0**	**$0**	**$0**	**$146,406**	**$794,218**

L	**Overflight Remote Sensing in Support of GCDAMP and LTEMP**								
L.1	Analysis and interpretation of overflight remote sensing data	$254,472	$12,000	$5,000	$0	$100,453	$0	$64,366	**$436,291**
L.2	Acquisition of overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
L.3	Acquisition of airborne lidar in conjunction with overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total L	**$254,472**	**$12,000**	**$5,000**	**$0**	**$100,453**	**$0**	**$64,366**	**$436,291**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$760,348	$16,000	$115,000	$0	$0	$0	$201,445	**$1,092,792**
M.2	Logistics staff	$442,515	$0	$0	$0	$40,551	$0	$101,225	**$584,291**
M.3	IT	$0	$0	$57,250	$0	$0	$0	$12,939	**$70,189**
	Total M	**$1,202,863**	**$16,000**	**$172,250**	**$0**	**$40,551**	**$0**	**$315,608**	**$1,747,272**
N	**Native Fish Population Dynamics**								
N.1	Sucker and dace distribution and demographics (SADDAD)	$0	$0	$0	$0	$0	$0	$0	**$0**
N.2	Predictive modeling and Decision support for native fishes	$0	$0	$0	$0	$0	$0	$0	**$0**
N.3	Evaluating dispersal and sources of mortality (Razorback sucker) using new technology	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total N	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
	Total (FY26)	**$5,915,119**	**$129,615**	**$576,906**	**$1,085,505**	**$1,448,220**	**$386,960**	**$1,785,261**	**$11,327,587**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$10,000,000**
	AMP Over/Under Budget								**($1,327,587)**
	Anticipated Carryover Funding Available								$0
	Other Carryover/non-AMP Funding								$0
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								($1,327,587)
	Lake Powell Water Quality Monitoring								
	Lake Powell water quality monitoring	$222,212	$0	$0	$0	$0	$0	$123,328	**$345,539**
	GCMRC Grand Total (w/ Lake Powell)	**$6,137,331**	**$129,615**	**$576,906**	**$1,085,505**	**$1,448,220**	**$386,960**	**$1,908,589**	**$11,673,126**

FY 2027

Fiscal Year 2027									
Project	Project Description	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
								23.40%	
A	**Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem**								
A.1	Stream gaging and hydrologic analyses	$210,769	$6,000	$6,000	$29,000	$0	$185,800	$58,914	**$496,483**
A.2	Continuous water quality parameters	$137,577	$1,000	$12,000	$27,400	$0	$30,900	$41,647	**$250,524**
A.3	Sediment transport and budgeting	$388,653	$6,000	$48,000	$28,000	$0	$165,900	$110,133	**$746,686**
	Total A	**$737,000**	**$13,000**	**$66,000**	**$84,400**	**$0**	**$382,600**	**$210,694**	**$1,493,693**
B	**Sandbar and Sediment Storage Monitoring and Research**								
B.1	Sandbar and campsite monitoring with topographic surveys and remote cameras	$275,431	$2,000	$4,000	$32,895	$23,500	$0	$74,257	**$412,083**
B.2	Bathymetric and topographic mapping for monitoring sediment storage and riverbed dynamics	$456,419	$2,000	$2,000	$0	$18,800	$0	$108,302	**$587,522**
B.3	Control network and survey support	$0	$0	$0	$0	$0	$0	$0	**$0**
B.4	Streamflow, sediment, and sandbar modeling	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total B	**$731,850**	**$4,000**	**$6,000**	**$32,895**	**$42,300**	**$0**	**$182,559**	**$999,604**
C	**Riparian Vegetation Monitoring and Research**								
C.1	Ground-based riparian vegetation monitoring	$149,838	$1,615	$3,500	$88,103	$14,112	$0	$57,298	**$314,466**
C.2	Determining hydrological tolerances and management tools for plant species of interest	$12,060	$0	$0	$0	$48,820	$0	$4,287	**$65,167**
C.3	Predictive models and synthesis	$11,486	$0	$0	$0	$50,312	$0	$4,197	**$65,995**
C.4	Biogeomorphic Linkages between streamflow, sediment transport, and vegetation composition	$0	$0	$0	$0	$0	$0	$0	**$0**
C.5	Vegetation management decision support	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total C	**$173,384**	**$1,615**	**$3,500**	**$88,103**	**$113,244**	**$0**	**$65,782**	**$445,628**
D	**Effects of Dam Operations and Vegetation Management for Archaeological Sites**								
D.1	Monitoring the effects of dam operations on archaeological sites	$205,526	$10,000	$20,000	$37,030	$0	$0	$63,778	**$336,335**
D.2	Monitoring landscape-scale ecosystem change with repeat photography	$24,518	$3,000	$1,000	$0	$0	$0	$6,673	**$35,191**
D.3	Evaluating effects of LTEMP non-flow actions and other experimental vegetation management on archaeological sites	$78,430	$9,000	$2,500	$0	$0	$0	$21,044	**$110,974**
D.4	Pilot study to evaluate potential to extract cultural and ecological information from Colorado River deposits using eDNA and pollen	$0	$0	$0	$0	$0	$0	$0	**$0**
D.5	Monitoring petroglyphs and pictographs with photogrammetry and lidar	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total D	**$308,474**	**$22,000**	**$23,500**	**$37,030**	**$0**	**$0**	**$91,495**	**$482,499**
E	**Controls on Ecosystem Productivity: Nutrients, Flow, and Temperature**								
E.1	Phosphorus budgeting in the Colorado River	$103,785	$2,000	$3,500	$0	$0	$0	$25,573	**$134,857**
E.2	Rates and composition of primary producers in the Colorado River	$89,894	$6,500	$18,044	$1,750	$0	$0	$27,188	**$143,376**
E.3	Understanding the energetic basis of the food web in Western Grand Canyon	$0	$0	$0	$0	$0	$0	$0	**$0**
E.4	Productivity at higher trophic levels	$53,426	$0	$3,000	$0	$0	$0	$13,204	**$69,629**
	Total E	**$247,104**	**$8,500**	**$24,544**	**$1,750**	**$0**	**$0**	**$65,964**	**$347,863**

F	**Aquatic Invertebrate Ecology**								
F.1	Invertebrate and bat monitoring in Marble and Grand Canyons	$252,296	$4,500	$39,000	$0	$0	$0	$69,216	**$365,012**
F.2	Aquatic invertebrate monitoring in Glen Canyon	$163,840	$3,500	$4,500	$875	$0	$0	$40,415	**$213,131**
F.3	Aquatic invertebrate monitoring of Grand Canyon tributaries	$26,549	$2,500	$0	$15,411	$49,350	$0	$11,884	**$105,694**
F.4	Invertebrate and fish diet studies	$77,691	$2,500	$2,000	$15,411	$0	$0	$22,839	**$120,441**
	Total F	**$520,376**	**$13,000**	**$45,500**	**$31,697**	**$49,350**	**$0**	**$144,355**	**$804,278**
G	**Humpback Chub Population Dynamics throughout the Colorado River Ecosystem**								
G.1	Humpback chub population modeling	$215,493	$8,000	$5,000	$0	$0	$0	$53,467	**$281,960**
G.2	Annual spring/fall HBC abundance estimates in the lower 13.6 km of the LCR	$3,228	$0	$20,222	$81,204	$399,455	$0	$36,473	**$540,582**
G.3	Juvenile chub monitoring near the LCR confluence (JCM-East)	$162,811	$2,000	$30,156	$324,740	$0	$0	$121,612	**$641,319**
G.4	Remote PIT-tag array monitoring in the LCR	$25,826	$0	$2,000	$2,000	$0	$0	$6,979	**$36,805**
G.5	Monitoring humpback chub aggregation relative abundance and distribution	$3,228	$0	$12,436	$66,912	$147,083	$0	$23,735	**$253,395**
G.6	Juvenile chub monitoring - Western Grand Canyon (JCM-West)	$0	$0	$0	$0	$0	$0	$0	**$0**
G.7	Chute Falls translocations	$0	$0	$0	$0	$0	$0	$0	**$0**
G.8	Sampling of springs in the upper LCR	$0	$0	$0	$0	$0	$0	$0	**$0**
G.9	Movement in western Grand Canyon from system-wide antenna monitoring	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total G	**$410,587**	**$10,000**	**$69,814**	**$474,856**	**$546,538**	**$0**	**$242,266**	**$1,754,061**
H	**Salmonid Research and Monitoring**								
H.1	Rainbow trout fishery monitoring in Glen Canyon	$7,920	$0	$0	$0	$88,000	$0	$4,493	**$100,413**
H.2	Experimental flow assessment of trout recruitment (TRGD)	$87,553	$2,500	$68,800	$118,998	$0	$0	$65,017	**$342,869**
H.3	Salmonid modeling	$76,163	$0	$6,000	$0	$0	$0	$19,226	**$101,390**
	Total H	**$171,637**	**$2,500**	**$74,800**	**$118,998**	**$88,000**	**$0**	**$88,737**	**$544,671**
I	**Non-native Invasive Species Monitoring and Research**								
I.1	System-wide native fishes and invasive aquatic species monitoring	$7,639	$0	$3,100	$114,150	$217,550	$0	$35,751	**$378,190**
I.2	Estimating kinship and spawner abundance of warm-water non-natives	$73,978	$2,000	$200	$0	$140,445	$0	$22,039	**$238,662**
I.3	Identifying emerging threats to the Colorado River Ecosystem using environmental DNA	$121,288	$150	$3,300	$15,266	$79,704	$0	$35,152	**$254,860**
I.4	Modeling population dynamics and improving forecasting tools for smallmouth bass and other non-native fish	$212,889	$200	$1,800	$0	$0	$0	$50,284	**$265,173**
	Total I	**$415,794**	**$2,350**	**$8,400**	**$129,416**	**$437,699**	**$0**	**$143,226**	**$1,136,885**
J	**Socioeconomic Research**								
J.1	Integrated models for adaptive management	$152,410	$7,500	$20,000	$0	$0	$0	$42,099	**$222,009**
J.2	Recreation monitoring and research	$117,873	$5,500	$10,000	$0	$0	$0	$31,209	**$164,582**
J.3	Tribal resources research	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total J	**$270,283**	**$13,000**	**$30,000**	**$0**	**$0**	**$0**	**$73,308**	**$386,591**
K	**Geospatial Science, Data Management, and Technology**								
K.1	Enterprise GIS, geospatial analysis, and processing	$184,042	$4,000	$5,600	$0	$0	$0	$45,312	**$238,954**
K.2	Data management and database administration	$322,061	$1,800	$3,000	$0	$0	$0	$76,485	**$403,346**
K.3	Data telemetry and field engineering	$161,430	$3,500	$6,550	$0	$0	$0	$40,126	**$211,606**
	Total K	**$667,532**	**$9,300**	**$15,150**	**$0**	**$0**	**$0**	**$161,924**	**$853,906**

L	**Overflight Remote Sensing in Support of GCDAMP and LTEMP**								
L.1	Analysis and interpretation of overflight remote sensing data	$272,285	$12,000	$5,000	$0	$103,396	$0	$70,795	**$463,476**
L.2	Acquisition of overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
L.3	Acquisition of airborne lidar in conjunction with overflight remote sensing imagery	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total L	**$272,285**	**$12,000**	**$5,000**	**$0**	**$103,396**	**$0**	**$70,795**	**$463,476**
M	**Leadership, Management, and Support**								
M.1	Leadership, management, and support	$813,572	$16,000	$115,000	$0	$0	$0	$221,030	**$1,165,602**
M.2	Logistics staff	$473,491	$0	$0	$0	$42,798	$0	$112,081	**$628,370**
M.3	IT	$0	$0	$65,750	$0	$0	$0	$15,386	**$81,136**
	Total M	**$1,287,063**	**$16,000**	**$180,750**	**$0**	**$42,798**	**$0**	**$348,496**	**$1,875,107**
N	**Native Fish Population Dynamics**								
N.1	Sucker and dace distribution and demographics (SADDAD)	$0	$0	$0	$0	$0	$0	$0	**$0**
N.2	Predictive modeling and Decision support for native fishes	$0	$0	$0	$0	$0	$0	$0	**$0**
N.3	Evaluating dispersal and sources of mortality (Razorback sucker) using new technology	$0	$0	$0	$0	$0	$0	$0	**$0**
	Total N	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
	GCMRC AMP Total (FY27)	**$6,213,369**	**$127,265**	**$552,958**	**$999,145**	**$1,423,326**	**$382,600**	**$1,889,600**	**$11,588,263**
	Anticipated AMP Funding Available (80.0% and 0% CPI)								**$10,000,000**
	AMP Over/Under Budget								**($1,588,263)**
	Anticipated Carryover Funding Available								$0
	Other Carryover/non-AMP Funding								$0
	Native Fish Conservation Contingency Fund								$0
	GCMRC AMP Total Over/Under Budget (w/ Carryover and Fish Funds)								($1,588,263)
	Lake Powell Water Quality Monitoring								
	Lake Powell water quality monitoring	$225,702	$0	$0	$0	$0	$0	$126,393	**$352,095**
	GCMRC Grand Total (w/ Lake Powell)	**$6,439,071**	**$127,265**	**$552,958**	**$999,145**	**$1,423,326**	**$382,600**	**$2,015,993**	**$11,940,358**

Appendix 2. Experimental Fund Summaries by Year

FY 2025

Fiscal Year 2025								
Appendix 2 Experimental Fund Projects	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							21.80%	
A.4. HFE Experimental Fund	$119,907	$2,000	$20,000	$45,200	$0	$0	$40,789	**$227,896**
Total A	**$119,907**	**$2,000**	**$20,000**	**$45,200**	**$0**	**$0**	**$40,789**	**$227,896**
B.5.1. Extended duration Fall HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$40,551	$3,000	$1,000	$96,787	$69,325	$0	$32,891	**$243,554**
B.5.2. Proactive Spring HFE (1 set of sandbar surveys w/o bathymetry)	$37,266	$1,500	$1,000	$55,144	$36,425	$0	$21,783	**$153,118**
B.5.3. Proactive Spring HFE (1 set of sandbar surveys with bathymetry)	$37,266	$1,500	$1,000	$61,858	$69,325	$0	$24,234	**$195,182**
B.5.4. Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$43,836	$3,000	$1,000	$117,611	$69,325	$0	$38,147	**$272,919**
B.5.5. Channel response to HFE in western Grand Canyon (4 surveys around fall HFE)	$33,981	$1,000	$1,000	$4,587	$22,325	$0	$9,514	**$72,406**
Total B	**$192,900**	**$10,000**	**$5,000**	**$335,986**	**$266,725**	**$0**	**$126,569**	**$937,180**
C.5. Experimental Vegetation Treatment Support	$10,032	$0	$0	$0	$4,001	$0	$2,307	**$16,341**
C.6. Plant physiological responses to experimental flows	$0	$450	$400	$9,362	$0	$0	$2,226	**$12,438**
C.7. Effects of plants on flow velocity and sand deposition	$56,933	$0	$0	$14,932	$0	$0	$15,667	**$87,532**
Total C	**$66,966**	**$450**	**$400**	**$24,294**	**$4,001**	**$0**	**$20,200**	**$116,311**
D.6. Post-HFE surveys	$30,104	$250	$0	$0	$0	$0	$6,617	**$36,971**
Total D	**$30,104**	**$250**	**$0**	**$0**	**$0**	**$0**	**$6,617**	**$36,971**
I.5. Evaluating the efficacy of flow experiments in the LTEMP sEIS to control smallmouth bass	$31,004	$1,800	$5,200	$38,142	$94,478	$0	$19,434	**$190,059**
I.6. Determining hatch dates of larval smallmouth bass in response to LTEMP sEIS flow experiments	$19,480	$1,500	$200	$11,102	$117,500	$0	$10,562	**$160,344**
Total I	**$50,484**	**$3,300**	**$5,400**	**$49,244**	**$211,978**	**$0**	**$29,997**	**$350,403**
Total Experimental Fund (FY25)	**$460,360**	**$16,000**	**$30,800**	**$454,724**	**$482,705**	**$0**	**$224,172**	**$1,668,761**

FY 2026

	Fiscal Year 2026							
Appendix 2 Experimental Fund Projects	**Salaries**	**Travel & Training**	**Operating Expenses**	**Logistics Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden**	**Total**
							22.60%	
A.4. HFE Experimental Fund	$128,300	$2,050	$20,000	$46,700	$0	$0	$44,533	**$241,584**
Total A	**$128,300**	**$2,050**	**$20,000**	**$46,700**	**$0**	**$0**	**$44,533**	**$241,584**
B.5.1. Extended duration Fall HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$43,389	$3,000	$1,000	$99,980	$69,325	$0	$35,385	**$252,079**
B.5.2. Proactive Spring HFE (1 set of sandbar surveys w/o bathymetry)	$39,875	$1,500	$1,000	$56,966	$36,425	$0	$23,544	**$159,309**
B.5.3. Proactive Spring HFE (1 set of sandbar surveys with bathymetry)	$39,875	$1,500	$1,000	$63,843	$69,325	$0	$26,085	**$201,628**
B.5.4. Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$46,904	$3,000	$1,000	$113,932	$69,325	$0	$39,333	**$273,494**
B.5.5. Channel response to HFE in western Grand Canyon (4 surveys around fall HFE)	$36,360	$1,000	$1,000	$4,667	$22,325	$0	$10,394	**$75,746**
Total B	**$206,403**	**$10,000**	**$5,000**	**$339,388**	**$266,725**	**$0**	**$134,740**	**$962,256**
C.5. Experimental Vegetation Treatment Support	$10,735	$0	$0	$0	$4,884	$0	$2,573	**$18,191**
C.6. Plant physiological responses to experimental flows	$0	$450	$400	$9,774	$0	$0	$2,401	**$13,025**
C.7. Effects of plants on flow velocity and sand deposition	$60,919	$0	$0	$15,432	$0	$0	$17,255	**$93,605**
Total C	**$71,653**	**$450**	**$400**	**$25,206**	**$4,884**	**$0**	**$22,229**	**$124,822**
D.6. Post-HFE surveys	$32,211	$250	$0	$0	$0	$0	$7,336	**$39,797**
Total D	**$32,211**	**$250**	**$0**	**$0**	**$0**	**$0**	**$7,336**	**$39,797**
I.5. Evaluating the efficacy of flow experiments in the LTEMP sEIS to control smallmouth bass	$33,175	$1,800	$5,200	$39,386	$94,478	$0	$20,815	**$194,854**
I.6. Determining hatch dates of larval smallmouth bass in response to LTEMP sEIS flow experiments	$20,844	$1,500	$200	$11,316	$117,500	$0	$11,177	**$162,537**
Total I	**$54,018**	**$3,300**	**$5,400**	**$50,702**	**$211,978**	**$0**	**$31,992**	**$357,391**
Total Experimental Fund (FY26)	**$492,585**	**$16,050**	**$30,800**	**$461,996**	**$483,587**	**$0**	**$240,831**	**$1,725,850**

FY 2027

Fiscal Year 2027								
Appendix 2 Experimental Fund Projects	Salaries	Travel & Training	Operating Expenses	Logistics Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
							23.40%	
A.4. HFE Experimental Fund	$137,281	$2,100	$20,000	$48,100	$0	$0	$48,551	**$256,032**
Total A	**$137,281**	**$2,100**	**$20,000**	**$48,100**	**$0**	**$0**	**$48,551**	**$256,032**
B.5.1. Extended duration Fall HFE (daily surveys during HFE + 1 set sandbar surveys w/o bathymetry)	$46,427	$3,000	$1,000	$103,201	$69,325	$0	$38,029	**$260,982**
B.5.2. Proactive Spring HFE (1 set of sandbar surveys w/o bathymetry)	$42,666	$1,500	$1,000	$58,806	$36,425	$0	$25,422	**$165,818**
B.5.3. Proactive Spring HFE (1 set of sandbar surveys with bathymetry)	$42,666	$1,500	$1,000	$65,259	$69,325	$0	$27,919	**$207,669**
B.5.4. Variation in HFE downramp rate (2 sets of sandbar surveys w/o bathymetry)	$50,188	$3,000	$1,000	$117,611	$69,325	$0	$42,281	**$283,404**
B.5.5. Channel response to HFE in western Grand Canyon (4 surveys around fall HFE)	$38,905	$1,000	$1,000	$4,749	$22,325	$0	$11,353	**$79,331**
Total B	**$220,851**	**$10,000**	**$5,000**	**$349,626**	**$266,725**	**$0**	**$145,003**	**$997,205**
C.5. Experimental Vegetation Treatment Support	$11,486	$0	$0	$0	$5,032	$0	$2,839	**$19,356**
C.6. Plant physiological responses to experimental flows	$0	$450	$400	$10,118	$0	$0	$2,567	**$13,535**
C.7. Effects of plants on flow velocity and sand deposition	$65,183	$0	$0	$15,933	$0	$0	$18,981	**$100,098**
Total C	**$76,669**	**$450**	**$400**	**$26,051**	**$5,032**	**$0**	**$24,386**	**$132,988**
D.6. Post-HFE surveys	$34,466	$250	$0	$0	$0	$0	$8,124	**$42,839**
Total D	**$34,466**	**$250**	**$0**	**$0**	**$0**	**$0**	**$8,124**	**$42,839**
I.5. Evaluating the efficacy of flow experiments in the LTEMP sEIS to control smallmouth bass	$35,497	$1,800	$5,200	$40,638	$94,478	$0	$22,288	**$199,901**
I.6. Determining hatch dates of larval smallmouth bass in response to LTEMP sEIS flow experiments	$22,303	$1,500	$200	$11,536	$117,500	$0	$11,841	**$164,880**
Total I	**$57,799**	**$3,300**	**$5,400**	**$52,174**	**$211,978**	**$0**	**$34,129**	**$364,781**
Total Experimental Fund (FY27)	**$527,066**	**$16,100**	**$30,800**	**$475,951**	**$483,735**	**$0**	**$260,193**	**$1,793,845**