Proceedings of the Fiscal Year 2023 Annual Reporting Meeting to the Glen Canyon Dam Adaptive Management Program

January 23-25, 2024, Phoenix, Arizona

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

Cover: Colorado River River Mile 41.9, looking upstream toward Bert's Canyon
with late afternoon sunlight reflecting off the water
Photo by Emily Palmquist, U.S. Geological Survey, Southwest Biological Science Center

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U.S. Geological Survey

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Introduction

The following is U.S. Geological Survey (USGS) Southwest Biological Science Center (SBSC) Grand Canyon Monitoring and Research Center's (GCMRC) FY 2023 annual report. This report summarizes work conducted, scientific papers, government documents, and data collected by GCMRC projects during FY 2023 with tie-in to previous fiscal years as appropriate, and presented to the Glen Canyon Dam Adaptive Management Program (GCDAMP) in several meetings during FY 2023. The report will be presented at the FY 2023 Annual Reporting Meeting on January 23-25, 2024, to the GCDAMP, including the Bureau of Reclamation, cooperators, and stakeholders to inform the Technical Work Group of science activities[1] conducted in support of GCDAMP.

This document contains project reports for activities conducted in FY 2023[2] as part of GCMRC's FY 2021-23 Triennial Work Plan[3]. The research and monitoring activities described in this document help inform progress toward the 11 resource goals identified in the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement and Record of Decision (Table 1). Tables 1 and 2 present crosswalks between GCMRC's projects and the LTEMP Resource Goals, including connections to dam operations and experimental actions.

This document also reports on USGS activities conducted as part of the Lake Powell Water Quality Monitoring Program (Appendix 1). The Deliverables (Products) and project budgets are presented in each project and compiled in Appendices 2 and 3.

Below, we highlight some key findings from GCMRC scientists and collaborators in FY 2023.

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[1] All handling of fish by GCMRC and all cooperating agencies was done according to standardized methods developed specifically for Grand Canyon (Persons and others, 2015). These methods describe how to handle fish safely and ethically during monitoring and research activities. SBSC is in the process of standing up an Institutional Animal Care and Use Committee (IACUC) per new requirements of the US Geological Survey's Ecosystem Mission Area (https://www.usgs.gov/mission-areas/ecosystems/usgs-ecosystems-mission-area-animal-welfare-assurance).

[2] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[3] U.S. Department of the Interior, 2020, Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2021-2023—Final approved by the Secretary of the Interior—December 2, 2020: Flagstaff, Ariz., U.S. Geological Survey, Grand Canyon MonitoReclamation, Upper Colorado Region, 384 p., http://gcdamp.com/images_gcdamp_com/5/5d/GCMRC_TWP2021-23_December2_2020_ApprovedBySecretary.pdf

Several GCMRC projects provided substantial support for planning and monitoring the April 2023 High-Flow Experiment (HFE). This work included collection of, processing, and reporting on Paria River sediment input and main-stem sediment supply conditions (Project A); streamflow, sediment, and sandbar modeling to develop the HFE hydrograph (Project B); and monitoring sandbar response in Marble and Grand Canyons and riverbed change in western Grand Canyon (Project B). Preliminary results indicate that the HFE resulted in widespread sediment deposition on sandbars and improved conditions for camping, despite subsequent erosion that occurred during the summer 2023 reservoir-balancing flows. Photographs showing sandbar response can be viewed at https://www.usgs.gov/apps/sandbar/.

Historic low elevations in Lake Powell during the spring of FY 2023 combined with a larger than average spring inflow set up a low dissolved oxygen event in the reservoir. These events resulted in likely record low dissolved oxygen in dam releases (minimum of ~1.8 mg/L in early October) and a record 116 days where dissolved-oxygen concentrations in releases remained below 5 mg/L (data after June 1 have not been processed for rigorous quality assurance). While water release temperatures were not as warm as in FY 2022, mean daily water temperature of dam releases was above 16 °C, starting in mid-July, and did not likely drop below this value until November 18, thereby resulting in beneficial conditions for smallmouth bass and other warm-water nonnative fishes for more than four months.

In FY 2023, native fishes continued to dominate fish catch in Grand Canyon. Models focused primarily on evaluation of the humpback chub (*Gila cypha*) life history in western Grand Canyon and results suggested that these fish exhibit relatively fast growth and high subadult survival compared to Little Colorado River spawning humpback chub in eastern Grand Canyon. However, adult apparent survival was low in western Grand Canyon, suggesting either that true survival is low or emigration is high (Dzul and others, 2023). Warm-water nonnative fishes continued to be captured throughout Grand and Glen Canyons in FY 2023. Most concerningly, nonnative smallmouth bass (*Micropterus dolomieu*) were captured in Glen Canyon and also downstream of the Paria River in Grand Canyon. Additionally, increases in catch of nonnative green sunfish (*Lepomis cyanellus*) occurred in the juvenile chub monitoring (JCM) east reach.

During FY 2023, Sankey and others (2023) reported on long-term monitoring of 362 Colorado River Corridor (CRC) archaeological sites in Grand Canyon National Park and synthesized the results with topographic changes reported by Caster and others (2022). Results indicated a loss of preservation potential for archaeological sites due to the long-term operations of the Glen Canyon Dam (Sankey and others, 2023). However, where active management has recently been conducted through vegetation removal efforts by the NPS, geomorphic conditions appear less degraded and may provide another management tool that can help offset erosion of archaeological sites.

In FY 2023, Metcalfe and others (2023) documented the connection between the Colorado River aquatic food base and bat activity. The paper analyzed 1,428 paired insect abundance and bat activity samples collected by community scientists from 2017-2020 and found that bat activity (# of calls per hour) was strongly and positively related to the abundance of adult midges (Diptera) in Grand Canyon. Food web and fish diet studies from the Colorado River have shown that midges are a key prey item supporting the growth of native (e.g., humpback chub, flannelmouth sucker) and desired nonnative fishes (i.e., rainbow trout; see Kennedy and others, 2013). The paper by Metcalfe and others highlights the important role that adult midges play in supporting bat populations in Grand Canyon and demonstrates the power of community science as a tool for ecosystem monitoring.

During FY 2023, in cooperation with Glen Canyon National Recreation Area and Arizona Game and Fish Department, GCRMC continued to monitor and advise on modifications to the brown trout incentivized harvest program. Results indicate an increase in angler trips and brown trout catch with additional incentives, including a significant increase in brown trout catch by a limited number of highly proficient anglers. FY 2023 also highlighted the importance of river flows for recreation and the challenges associated with lower flows. In September 2023 flows reached a minimum, 5,000 cfs released overnight, near the end of the motorized boater season. These lower flows were difficult for commercial operators to navigate, and an illustration of challenges recreational boaters will face under low flows.

Research on riparian plant communities continued in FY 2023 through observational monitoring, physiological experiments, and predictive modeling. A USGS Status and Trends report was published based on annual monitoring data from 2014 through 2019 (Palmquist and others, 2023a), which discussed vegetation compositional differences throughout the study area and trends in vegetation metrics. The results of an inundation experiment on arrowweed *(Pluchea sericea)* indicated that this species is hindered by long-term inundation and that some genotypes grow larger and faster than others (Palmquist and others, 2023b). Previous niche modeling work was leveraged to rapidly develop predicted species responses to alternative dam operations in support of the Near-term Colorado River Operations Supplemental Environmental Impact Statement and indicates that the loss of HFEs would have a much greater impact on riparian plant communities than redistribution of release volumes throughout the year.

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Table 1: LTEMP Resource Goals

Archaeological and Cultural Resources

LTEMP Resource Goal	Project
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.	Addressed by **Projects A and D** on how flow and non-flow actions will affect the long-term preservation of cultural resources and other culturally valued and ecologically important landscape elements located within the Colorado River ecosystem (CRe).

Natural Processes

LTEMP Resource Goal	Project
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.	Addressed by **Projects A, C, E, and F** through 1) monitoring of stage, discharge, water temperature, specific conductance, dissolved oxygen, turbidity, suspended-sediment concentration, and particle size at stream/river locations throughout the Colorado River ecosystem (CRe), 2) monitoring changes in riparian vegetation using field-collected data and digital imagery (Project L), developing predictive models of vegetation composition as it relates to hydrological regime, and providing monitoring protocols and decision support tools for active vegetation management, 3) identifying processes that drive spatial and temporal variation in nutrients and temperature within the CRe and establishing quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels, and 4) tracking the response of aquatic food base organisms to flow and non-flow actions.

Humpback Chub

LTEMP Resource Goal	Project
Meet humpback chub recovery goals, including maintaining a self-sustaining population, spawning habitat, and aggregations in the Colorado River and its tributaries below the Glen Canyon Dam.	Addressed by **Projects A, E, F, G, I, and J** through 1) identifying processes that drive spatial and temporal variation in nutrients and temperature within the Colorado River ecosystem (CRe) and establishing quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels, 2) tracking the response of aquatic food base organisms to flow and non-flow actions, 3) monitoring of humpback chub populations, dynamics, and condition in aggregations in the main-stem Colorado River both upstream and downstream of the confluence with the Little Colorado River and within the Little Colorado River, 4) monitoring the status and trends of native and nonnative fish that occur in the CRe from Lees Ferry to Lake Mead, and 5) identifying preferences for, and values of, native fish like the humpback chub and evaluating how preferences and values are influenced by Glen Canyon Dam operations.

Hydropower and Energy

LTEMP Resource Goal	Project
Maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources.	Addressed by **Project N** through identifying, coordinating, and collaborating on monitoring and research opportunities associated with operational experiments at Glen Canyon Dam to meet hydropower and energy resource objectives.

Other Native Fish

LTEMP Resource Goal	Project
Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.	Addressed by **Projects A, E, F, G, and I** through 1) identifying processes that drive spatial and temporal variation in nutrients and temperature within the Colorado River ecosystem and establishing quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels, 2) tracking the response of aquatic food base organisms to flow and non-flow actions, 3) monitoring of humpback chub populations, dynamics, and condition in aggregations in the main-stem Colorado River both upstream and downstream of the confluence with the Little Colorado River and within the Little Colorado River, and 4) monitoring the status and trends of native and nonnative fish that occur in the Colorado River ecosystem from Lees Ferry to Lake Mead.

Sediment

LTEMP Resource Goal	Project
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.	Addressed by **Projects A, B, D, and L** through 1) monitoring of stage, discharge, water temperature, specific conductance, dissolved oxygen, turbidity, suspended-sediment concentration, and particle size at stream/river locations in the Glen, Marble, and Grand Canyon reaches and 2) tracking the effects of experimental actions such as High-Flow Experiments (HFEs) on sandbars, monitoring the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and investigating the interactions between dam operations and sand transport and eddy sandbar dynamics.

Recreational Experience

LTEMP Resource Goal	Project
Maintain and improve the quality of recreational experiences for the users of the Colorado River ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.	Addressed by **Projects A, B, C, and H** through 1) tracking the effects of experimental actions such as HFEs on sandbars, monitoring the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and investigating the interactions between dam operations and sand transport, and eddy sandbar dynamics, 2) monitoring changes in riparian vegetation using field-collected data and digital imagery (Project L), developing predictive models of vegetation composition as it relates to hydrological regime, and providing monitoring protocols and decision support tools for active vegetation management, and 3) monitoring the status and trends of both rainbow and brown trout upstream of Lees Ferry in Glen Canyon, as well as increasing understanding of key factors such as density and recruitment, prey availability, and variables that control the abundance and growth of the trout population.

Tribal Resources

LTEMP Resource Goal	Project
Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.	Addressed by **Project J** through identifying Tribes' preferences for, and values of, downstream resources and evaluating how these preferences and values are influenced by Glen Canyon Dam operations.

Rainbow Trout Fishery

LTEMP Resource Goal	Project
Achieve a healthy, high-quality recreational rainbow trout fishery in Glen Canyon and reduce or eliminate downstream trout migration consistent with National Park Service fish management and Endangered Species Act compliance.	Addressed by **Project A, E, F, G, and H** through 1) monitoring the status and trends of both rainbow and brown trout upstream of Lees Ferry in Glen Canyon, as well as increasing understanding of key factors such as density and recruitment, prey availability, and variables that control the abundance and growth of the trout population, 2) identifying processes that drive spatial and temporal variation in nutrients and temperature within the Colorado River ecosystem and establishing quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels, 3) tracking the response of aquatic food base organisms to flow and non-flow actions, and 4) monitoring of humpback chub populations, dynamics, and condition in aggregations in the main-stem Colorado River both upstream and downstream of the confluence with the Little Colorado River and within the Little Colorado River.

Nonnative Invasive Species

LTEMP Resource Goal	Project
Minimize or reduce the presence and expansion of aquatic nonnative invasive species.	Addressed by **Projects A, F, G, I, and J** through 1) tracking the response of aquatic food base organisms to flow and non-flow actions, 2) monitoring the status and trends of native and nonnative fish that occur in the Colorado River ecosystem from Lees Ferry to Lake Mead, 3) monitoring of humpback chub populations, dynamics, and condition in aggregations in the main-stem Colorado River both upstream and downstream of the confluence with the Little Colorado River and within the Little Colorado River, and 4) identifying preferences for, and values of, nonnative fish like the rainbow trout and evaluating how preferences and values are influenced by Glen Canyon Dam operations.

Riparian Vegetation

LTEMP Resource Goal	Project
Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.	Addressed by **Projects A, B, and C** through monitoring changes in riparian vegetation using field-collected data and digital imagery (Project L), developing predictive models of vegetation composition as it relates to hydrological regime, and providing monitoring protocols and decision support tools for active vegetation management.

Table 2: Project Elements in the FY 2021-23 Triennial Work Plan (next page)

Project Elements in the FY 2021-23 Triennial Work Plan that address some aspect of the Long-Term Experimental and Management Plan (LTEMP) Resource Goals relative to LTEMP dam operations and experimental actions. Gray boxes indicate no relevance.

LTEMP General Dam Operations & Experimental Actions / LTEMP Resource Goal	Archeological & Cultural Resources	Natural Processes	Humpback Chub	Hydropower & Energy	Other Native Fish	Recreational Experience	Sediment	Tribal Resources	Rainbow Trout Fishery	Nonnative Invasive Species	Riparian Vegetation
General dam operations	A.1 D.1/D.2 K. L.	A.1-2 E.1-3 F.1-4 K. L.	A.1-2 G.1-6 I.1 J.1 K. L.	N.1 K. L.	A.1-2 G.1-6 I.1 K. L.	A.1-3 B.1/B.2 J.1/J.3 K. L.	A.1/A.3 B.1/B.2/B.3 D.3 K. L.	D.3 K. L.	A.1-2 H.1/H.2/H.4 I.1 K. L.	A.1-2 H.3 I.1-3 K. L.	A.1 B.1 C.1/C.2/C.3 K. L.
Fall High-Flow Experiments (HFE) > 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	A.1/A.3 D.1/D.2	A.1-3 E.1-3 F.1/F.2	A.1-2 G.1-6 J.1	N.1	A.1-2 G.1-6 I.1	A.1-3 B.1/B.2/B.6 J.1/J.3	A.1/A.3 B.2/B.6		A.1-2 H.1/H.2/H.4	A.1-2 H.3 I.1-3	A.1/A.3 B.1 C.1/C.2/C.3
Fall HFE ≤ 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	A.1/A.3 D.1/D.2	A.1-3 E.1-3 F.1/F.2	A.1-2 G.1-6 J.1	N.1	A.1-2 G.1-6 I.1	A.1-3 B.1/B.2/B.6 J.1/J.3	A.1/A.3 B.2/B.6		A.1-2 H.1/H.2/H.4	A.1-2 H.3 I.1-3	A.1/A.3 B.1 C.1/C.2/C.3
Humpback chub translocation			G.7								
Larval humpback chub head-start program			G.7								
Macroinvertebrate production flows		A.1-3 F.1/F.2/F.4	A.1-2 F.4 G.1-6 J.1	N.1	A.1-2 F.4 G.1-6 I.1	J.3			A.1-2 F.4 H.1/H.2/H.4	A.1-2 I.1-3	
Mechanical removal of invasive fish											
Mechanical removal of rainbow trout from Little Colorado River reach											
Proactive spring HFE ≤ 45,000 ft³/s, in April, May or June	A.1/A.3 D.1/D.2	A.1-3 E.1-3 F.1/F.2	A.1-2 G.1-6 J.1	N.1	A.1-2 G.1-6 I.1	A.1-3 B.1/B.2/B.6 J.1/J.3	A.1/A.3 B.2/B.6		A.1-2 H.1/H.2/H.4	H.3 I.1-3	A.1/A.3 B.1 C.1/C.2/C.3
Riparian vegetation restoration	D.1/D.2					C.4 J.1/J.3					A.1 C.4
Spring HFE ≤ 45,000 ft³/s, in March or April	A.1/A.3 D.1/D.2	A.1-3 E.1-3 F.1/F.2	A.1-2 G.1-6 J.1	N.1	A.1-2 G.1-6 I.1	A.1-3 B.1/B.2/B.6 J.1/J.3	A.1/A.3 B.2/B.6		A.1-2 H.1/H.2/H.4	H.3 I.1-3	A.1/A.3 B.1 C.1/C.2/C.3
Trout management flows				N.1					A.1 H.1/H.2/H.4	A.1 H.3	A.1 B.1 C.1/C.2/C.3
Spring disturbance flow	A.1/A.3 O.3	A.1-3 O.1/O.5	A.1-2 O.7	O.9	A.1-2 O.7	A.1-3 O.8/O.10	A.1/A.3 O.2/O.10	O.2	A.1-2 O.6	A.1-2 O.6	A.1 B.1 O.4

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

Project Lead	David Topping	**Principal Investigator(s)** (PI)	David Topping, USGS, GCMRC Ronald Griffiths, USGS, GCMRC David Dean, USGS, GCMRC
Email	dtopping@usgs.gov		
Telephone	(928) 556-7396		

Goals and Objectives

The goal of Project A is to make high-resolution measurements of stage, discharge, water temperature, specific conductance, dissolved oxygen, turbidity, suspended-sediment concentration, and particle size at 8 main-stem and 16 tributary sites located throughout the Colorado River ecosystem (CRe). This project collects the data that directly link dam operations to the physical CRe. Project A's data are used to trigger and design High-Flow Experiments (HFEs) (Grams and others, 2015; U.S. Department of the Interior, 2011) and, more generally, to inform managers about the physical status of the Colorado River in the CRe and how this physical status is affected by Long-Term Experimental and Management Plan (LTEMP) dam operations in near real-time (U.S. Department of the Interior, 2016a, b). Therefore, in addition to addressing the LTEMP sediment goal, the data collection supports the LTEMP goals in the following nine resource areas: 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. Details of this ongoing project, including descriptions of the data-collection locations, are provided in the GCMRC FY 2021–23 Triennial Work Plan (TWP).

Science Questions Addressed & Results

There are two key hypotheses that guide the monitoring and research conducted under the 3 elements of Project A (listed in the next section of this report). These hypotheses directly address the LTEMP sediment goal and the nine other LTEMP goals listed in the Goals and Objectives section. Owing to the interlocking nature of the three elements of Project A, the hypotheses that guide Project A and the results from Project A cannot be easily segregated by element and are therefore described together in this section.

- **Hypothesis 1:** Glen Canyon Dam can be operated such that the sand resources in the CRe are sustainable.

- **Hypothesis 2:** 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.

The FY 2023 results from Project A, highlighted below, are provided in three presentations at professional science meetings, two journal articles (one published and one accepted pending minor revisions), two USGS reports (both *in press*), and two updated websites described in the list of Deliverables below. Owing to hiring delays, only some of the monitoring data collected by this project, including those associated with the April 2023 HFE, have been posted to the project website (https://www.gcmrc.gov/discharge_qw_sediment/) as of November 2023.

The laboratory processing of data used to finalize sediment loads is currently 8 months behind schedule; although all water-quality data have been collected, no water-quality data collected after June 2023 have been processed and posted to this website (because no water-quality specialist has yet been hired). In addition, despite adequate funding under the GCMRC FY 2021–23 TWP, Project A's website is currently unsupported by USGS staff. Consequently, it is unclear if this website will continue to operate and Project A will be able to meet its LTEMP, HFE, and SEIS obligations during FY 2024. The lack of website support was first brought to the attention of USGS managers in 2019; USGS management has so far been unsuccessful in developing a stable long-term solution for maintaining this tool that is critical for DOI river management. Given the multifaceted nature of Project A, only a few key results are listed herein.

- A new technique was developed for calculating sand bedload from repeat multibeam sonar maps using data collected by Projects A and B near the Colorado River above Diamond Creek near Peach Springs, AZ, gaging station (LeCoz and others, 2022). This particle-tracking-based method provides an improved way to inform the estimates of sand bedload in the continuous mass-balance sand budgets at http://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP (Topping and others, 2021; Griffiths and others, *in press*).
- A journal article on the hydrology, sediment transport, and geomorphology of Moenkopi Wash was accepted at Geomorphology pending minor revisions (Dean and Topping, accepted with minor revisions). Moenkopi Wash is important because it supplies roughly 1/3 of the sediment ultimately supplied by the Little Colorado River to the Colorado River, and because it is currently the source of most of the larger peak flows important for maintaining endangered fish habitat in the lowermost segment of the Little Colorado River. Nonnative vegetation expansion into the channel of Moenkopi Wash starting in the 1950s has trapped sediment, causing substantial channel narrowing and a reduction in the amount of sediment transported to the Little Colorado River.

- The Dean and Topping article shows that nonnative vegetation expansion can play a much larger role in controlling channel form and sediment transport than hydrologic change.
- A USGS Open-File Report completed during FY 2022 (Griffiths and others, *in press*) analyzes changes in sand storage during sediment years 2018–2020 (July 1, 2017, through June 30, 2020) and provides additional support for the result in Topping and others (2021) that multi-year net sand accumulation is only possible in the Colorado River between Lees Ferry and Diamond Creek during years when the tributary sand supply exceeds ~130% of average and dam-released discharges are below the 1964-2017 average. This Open-File Report extended the sediment-year 2003–2017 analyses in Topping and others (2021) through sediment year 2020. Even though dam releases were slightly below average during sediment years 2018–2020, the tributary sand supply was well below average during 2 of these 3 years, thereby leading to net erosion of sand from Marble Canyon during the sediment-year 2018–2020 period. Thus, as concluded in Topping and others (2021), maintaining a level of sand storage sufficient for maintaining sandbars in the Colorado River may require timing periods of higher and lower dam-released discharge based on tributary sand-supply conditions. Whether the sand resources of the Colorado River in Grand Canyon National Park can be sustainably managed in perpetuity therefore remains an open question (Topping and others, 2021).
- A USGS Professional Paper (Topping and others, *in press*) describing research conducted between 1998 and 2019, currently at the USGS publishing network, indicates that the changes in sand cross-sectional area among the cross sections at the Marble Canyon dam sites are generally consistent with the flux-based estimates and measurements showing ~24 million metric tons of sand erosion from Marble Canyon between the 1963 closure of Glen Canyon Dam and 2000, and relatively little net change in sand storage in Marble Canyon between 2000 and 2012. In addition, this Professional Paper shows that incision into the Lake Mead deltaic deposits at the Bridge Canyon dam sites appears to be limited by bed-sediment grain size and downstream hydraulic controls.
- During FY 2023, the following changes in sand mass (shown in tabular form in Table A1) occurred in the six reaches where continuous mass-balance sand budgets are constructed by Project A. Sand erosion dominated in the CRe during FY 2023. Although some of this erosion occurred in some river segments as sand was transferred from the channel to sandbars during the April HFE, most of this erosion occurred during the high equalization flows that were released from the dam during May–August 2023. The changes in sand mass in this table are preliminary and may change because of a large backlog of sediment samples to process. Data from (http://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP).

Table A1. Changes in sand mass during FY 2023 (provisional data, subject to change).

Segment	Change in sand mass in metric tons during FY 2023; interpretation of change, in bold, uses criteria from Topping and others (2021)
Upper Marble Canyon	-2,200,000±130,000 **Erosion**
Lower Marble Canyon	400,000±210,000 **Deposition**
Eastern Grand Canyon	-990,000±650,000 **Erosion**
East-Central Grand Canyon	1,100,000±430,000* **Deposition**
West-Central Grand Canyon	-550,000±380,000* **Erosion**
Western Grand Canyon and the Lake Mead Delta (Colorado River downstream from Diamond Creek)	4,000,000±200,000** **Deposition**

*Data used to compute these values end in late August 2023 because the Colorado River above National Canyon near Supai, AZ, gaging station has not been visited since August 30 at the time this report was completed.
** Data used to compute these values end in August 2023 because the post-August acoustical suspended-sediment measurements from the Colorado River above Diamond Creek near Peach Springs, AZ, gaging station had not been processed at the time this report was completed.

Project Elements

The results and hypothesis testing described above, are completed via collection, serving, and interpretation of data distributed among three Project Elements. The specific focus of each element is described in brief below, but please consult the FY 2021-23 Triennial Workplan for additional information on these and the other elements of Project A listed herein.

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.

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 six main-stem Colorado River gaging stations. This element also funds episodic measurements of specific conductance associated with suspended-sediment samples collected in tributaries.

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 gaging stations on the Colorado River and its tributaries. In addition, this Project Element funds interpretive work regarding the sand supply from the Paria and Little Colorado rivers, and interpretive work regarding the effect of dam operations on the sediment resources in the Colorado River between Glen Canyon Dam and Lake Mead.

References

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

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U.S. Department of the Interior, 2020, Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2021-2023—Final approved by the Secretary of the Interior—December 2, 2020: Flagstaff, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, and Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 384 p., http://gcdamp.com/images_gcdamp_com/5/5d/GCMRC_TWP2021-23_December2_2020_ApprovedBySecretary.pdf.

Project A Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$499,029	$10,000	$59,600	$0	$396,277	$71,778	**$1,036,684**
Actual Spent	$520,763	$2,857	$107,074	$0	$398,187	$79,612	**$1,108,493**
(Over)/Under Budget	**($21,734)**	**$7,143**	**($47,474)**	**$0**	**($1,910)**	**($7,834)**	**($71,809)**

COMMENTS
FY23 Comments: -Overspent Salaries during FY23 is due to shortfall in the budget for essential project staff. -Underspent Travel & Training was from reluctance to attend AGU during December 2022 owing to COVID-19 and from delaying planned international travel until FY 2024. -Overspent Operating Expenses was for instrument repairs and replacements initiated in Q4 FY22 that were completed in FY23. -Overspending to other USGS Centers is due to rising costs for database/website design at Fort Collins and and EROS Scienece centers.

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

Presentations:

Salter, G., Topping, D.J., Wright, S.A., Nelson, J.M., Mueller, E.R., and Grams, P.E., 2023, Numerical modeling of mud transport, storage, and release on the Colorado River, Arizona, *in* Proceedings of SEDHYD 2023, the Federal Interagency Sedimentation and Hydrologic Modeling Conference, St. Louis, Mo., May 8-12, 2023, https://www.sedhyd.org/2023Program/1/20.pdf.

Salter, G, Topping, D.J., Wright, S.A., Nelson, J.M, Mueller, E.R, Grams, P.E., 2023, The washload to bed-material load continuum—Transport, storage, and release of fine sediment in a large canyon-bound river: The 13th Symposium on River, Coastal, and Estuarine Morphodynamics, RCEM2023, Urbana-Champaign, Ill., September 25-28, 2023, https://uofi.box.com/s/58f97gz06sf490n4l9r6mfsmm7lxzihm.

Wood, M., Groten, J., Straub, T., Whealdon-Haught, D., Griffiths, R., Boldt, J.A., Lucena, Z., Brown, J., Suttles, S., and Dickhudt, P., 2023, State of the science and decision support for measuring suspended sediment with acoustic instrumentation, *in* Proceedings of SEDHYD 2023, the Federal Interagency Sedimentation and Hydrologic Modeling Conference, St. Louis, Mo., May 8-12, 2023, https://www.sedhyd.org/2023Program/1/15.pdf.

Journal Articles:

Le Coz, J., Perret, E., Camenen, B., Topping, D.J., Buscombe, D.D., Leary, K.C.P., Dramais, G., and

Grams, P.E., 2022, Mapping 2-D bedload rates throughout a sand-bed river reach from high-resolution acoustical surveys of migrating bedforms: Water Resources Research, v. 58, no. 11, e2022WR032434, p. 1-16, https://doi.org/10.1029/2022WR032434.

Dean, D.J., and Topping, D.J., *In Press*, The effects of vegetative feedbacks on flood shape, sediment transport, and geomorphic change in a dryland river—Moenkopi Wash, AZ: Geomorphology.

USGS Reports:

Topping, D.J., Hazel, J.E., Jr., Kaplinski, M., and Grams, P.E., *In Press*, Resurvey of the Marble Canyon and Bridge Canyon dam sites in Grand Canyon National Park—Dam-induced changes in sediment storage and evidence supporting recent pre-dam bedrock incision: U.S. Geological Survey Professional Paper.

Griffiths, R.E., Topping, D.J., and Unema, J.A., *In Press*, Changes in sand storage in the Colorado River in Grand Canyon National Park from July 2017 through June 2020: U.S. Geological Survey Open-File Report.

USGS Data Releases:

None in FY 2023.

Web Applications:

http://www.gcmrc.gov/discharge_qw_sediment/

Stage, discharge, sediment transport, water-quality, and sand-budget data are served through the USGS-GCMRC website. The database associated with this website is updated every day to month depending on data type. This web-based application provides stakeholders, scientists, and the public with the ability to perform interactive online data visualization and analysis, including the on-demand construction of sand budgets and duration curves. These capabilities are unique in the world.

http://waterdata.usgs.gov/nwis

Stage, discharge, and water-quality data collected at 9 gaging stations by the USGS Utah and Arizona Water Science Centers under project are posted to this website every hour.

Project B: Sandbar and Sediment Storage Monitoring and Research

Project Lead	Paul Grams	**Principal Investigator(s)** (PI)	Paul Grams, USGS, GCMRC Keith Kohl, USGS, GCMRC Robert Tusso, USGS, GCMRC Gerard Salter, USGS, GCMRC Matt Kaplinski, NAU Katherine Chapman, NAU Erich Mueller, SUU
Email	pgrams@usgs.gov		
Telephone	(928) 266-6096		

Goals and Objectives

The purposes of this project are to: a) track the effects of individual High-Flow Experiments (HFEs) on sandbars, b) monitor the cumulative effect of successive HFEs and intervening operations on sandbars, campsites, and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics. This project addresses LTEMP resource goals for sediment by measurements of sandbars and sand storage in the river channel and by developing predictive tools for sand transport and sandbar response to dam operations. This project also addresses goals for recreational experience by measurements of campsite area and evaluation of campsites by the community science Adopt-a-Beach program. Outcomes from this project will be used to evaluate the effectiveness of the HFE protocol included in the 2016 Long-Term Experimental and Management Plan Record of Decision (U.S. Department of the Interior, 2016a) with respect to fine sediment and sandbar condition.

Science Questions Addressed & Results

Project Elements

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

Project B.1 addresses the hypothesis that sandbar building during sand-enriched HFEs will exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained to result in long-term increases in sandbar volume and campsite area. This hypothesis is addressed through annual monitoring using topographic surveys, analysis of images from remote cameras, and advances in data management. The sandbar monitoring data consist of topographic surveys collected by total station (Hazel and others, 2022) and measurements of campsite area (Hadley and others, 2018). Data collected in October 2022 were presented at the Annual Reporting Meeting in January 2023, and the most recent data, collected in October 2023, will be presented at the Annual Reporting Meeting in January 2024. Images from the remote cameras were retrieved in October 2022, February 2023, May 2023 (following the April HFE), and October 2023.

The community science Adopt-a-Beach program was continued by the Grand Canyon River Guides.

In a recently completed summary of the sandbar monitoring data, Hazel and others (2022) showed that sand volume increased at 86% of the monitoring sites between 2004 and 2020, owing to the seven HFEs that occurred during that period. In contrast, net erosion occurred between 1990 and 2003 – a period that included only one HFE in 1996. These findings demonstrate that the sand-enriched HFEs implemented under the HFE Protocol and LTEMP EIS (U.S. Department of the Interior, 2016b) caused net increases in sandbar volume. Individually, each of the HFEs implemented since 2012 resulted in substantial deposition at all sandbar types (Mueller and others, 2018; Grams, 2019; Hazel and others, 2022).

The normalized volume of sand in Narrow and Medium Reattachment Bars averaged for the 2013-2021 period was 22% greater than for the 2009-2012 period. For Wide Reattachment Bars and Upper Pool Bars the normalized sand volume was 12% greater for the 2013-2021 period. Thus, even though many sites experienced erosion, much of the HFE-deposited sand persisted. Deposition of sand during HFEs resulted in temporary increases in campsite area; however, there was a net long-term decline in campsite area caused by vegetation encroachment (Hadley and others, 2018). Although vegetation encroachment reduces campsite area (Hadley and others, 2018), it also promotes deposition and sand retention as described in a recently completed study by Butterfield and others (2020).

Sandbars eroded between November 2018 and October 2022 (Figure B1). This erosion was caused both by dam operations and hillslope runoff during summer thunderstorms that created gullies and deposited debris on sandbar campsites. The HFE that was implemented in April 2023 filled many of these gullies and replenished eroded sand (Figure B2). In previous years, the annual sandbar surveys occurred approximately 11 months following each HFE, therefore HFE deposits experienced erosion from dam operations for nearly one year (Grams and others, 2018). In 2023, sandbar surveys were conducted 5 months after the HFE and during that period, HFE-deposited sandbars were subjected to reservoir balancing flows peaking at up to 20,000 ft^3/s, followed by relatively low flows in September. Thus, the timing of the October 2023 sandbar surveys will afford the opportunity to assess the effects of both the April HFE and reservoir balancing flows.

While HFEs have resulted in sandbar deposition and net increases in sandbar volume, campsite area has remained stable or decreases owing to vegetation expansion, which has been ongoing in Marble and Grand Canyons (Sankey and others, 2015; Hadley and others, 2018; Kasprak and others, 2018). In 2023, we began work to modernize the campsite area data set into a format that will allow for analyses of camp quality based on the size and number of campsites and their elevations relative to streamflow. These data will be used with overflight images (Project L) and sandbar topographic surveys to study the relative impacts of dam releases and vegetation encroachment on the ‘campability’ of sandbars in Grand Canyon.

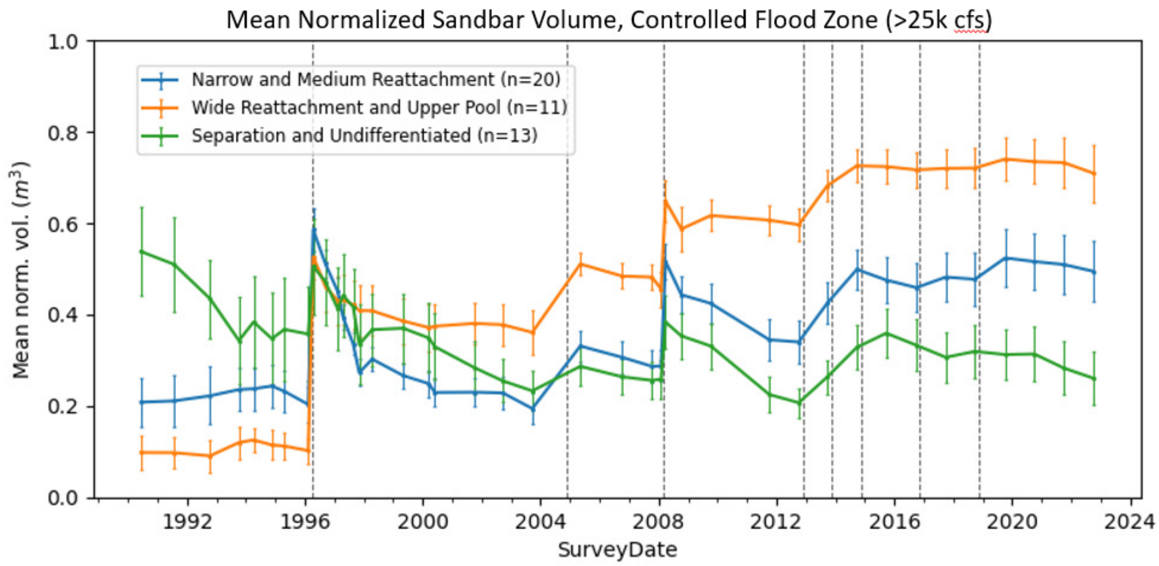

Figure B1. Mean normalized sandbar volume June 1990 to October 2022 for each site type. Methods and normalization procedure are described by Hazel and others (2022). Error bars are standard error. Vertical dashed lines show the timing of High-Flow Experiments (HFEs). Sites were measured immediately following HFEs in 1996, 2004, and 2008 only. Beginning in 2009, measurements were made once annually in October. The HFEs resulted in deposition and sandbar measurements indicate that there was net increase in sandbar volume between the beginning of the HFE protocol in 2012 and 2018 for Narrow and Medium Reattachment Bars and for Wide Reattachment and Upper Pool Bars. There has been no net increase in the size of Separation and Undifferentiated Bars. All bar types eroded between 2018 and 2022. Please see https://www.usgs.gov/apps/sandbar/sites for site locations and most recent data for individual sites.

Figure B2. Photographs of the sandbar monitoring site at River Mile 23.5 in Marble Canyon taken April 23, 2023 (top), and April 30, 2023 (bottom), immediately following the April High-Flow Experiment (HFE). Streamflow is from left to right. The HFE deposited sand that increased the sandbar elevation and filled the gullies that had formed in 2021 and 2022.

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

Project B.2 addresses the hypothesis that the supply of sand in sandbars, eddies, and on the riverbed will be maintained during the 20-year period of the LTEMP EIS, which will include sand-enriched HFEs, normal dam operations, and possibly include sustained high releases for reservoir balancing and/or equalization. This hypothesis is addressed by repeat measurements of sediment storage in sandbars, eddies, and on the riverbed at 3- to 10-year intervals with coupled topographic and bathymetric surveys. The measurements showing changes in sediment storage are also used to verify and complement the sediment budgets that are estimated based on measurements of suspended-sediment concentration as part of Project A. The continuous measurements of suspended-sediment concentration made in Project A allow sediment budgets to be computed for any time interval of interest, but because uncertainty accumulates, budgets computed over long time periods (more than a few years) have large uncertainty (Grams and others, 2013; 2019; Topping and others, 2021).

In Project B, sediment budgets are computed based on infrequent repeat measurements of channel bathymetry. Because uncertainty does not accumulate over time when using this method, changes in sediment storage that occur over long time periods (many years or decades) can be computed accurately and with well-constrained uncertainty.

During FY 2023, we continued processing of the channel mapping data set collected in 2022 and analysis/reporting of all previous channel mapping data sets (2011, 2012, 2013, 2016, 2017, and 2019). Results from these data sets will be presented at the Annual Reporting Meeting in January 2024. A new channel mapping data set was collected in the Western Grand Canyon Reach (RM 274-276). This effort consisted of three multibeam sonar surveys of the bed and lidar surveys of the subaerial banks before (April 25, 2023), during (April 27, 2023), and after (May 11, 2023) the Spring 2023 HFE. Repeat surveys of the channel bed were also conducted that will be used to estimate bedload transport in the study reach. Quality control checks on the bathymetric surveys are complete and the data are being processed. Processing of this data set will occur during FY 2024 with reporting on this data set occurring in the next work plan.

In late May and early June 2021, during the overflight for aerial images and concurrent 8,000 ft^3/s steady releases from Glen Canyon Dam, water surface elevations and bathymetry of the river centerline were collected from River Miles 0 to 282. In FY 2023 we continued to process, filter, and combine these data to create updated water surface and bed elevation profiles. Currently, we have a completed water surface profile (vertical error < 10 cm) for 246.61 river miles with missing or poor data for 34.84 river miles. We plan to complete the profile in FY 2024 using water surface elevations from the 1-m DEM and associated water's edge products collected during the overflight.

Preliminary analyses show these data will be usable for completing the gaps in the current 2021 profile while maintaining low vertical error. The 2021 centerline bathymetry data have been processed to represent bed elevation as depths below the water surface. However, the bathymetry data represented as true elevations will be finalized when the water surface profile is completed; some areas with GPS outages will be filled in with other data sources to assign elevations to the bathymetry. We will compare the centerline bathymetry data to bathymetry data collected on previous Channel Mapping expeditions. The completed 2021 water surface elevation profile will be used directly by projects that require information on inundation depth or height above water surface. The profile will also be used for new streamflow models to predict water surface elevation for the entire range of dam operations.

Element B.3. Control Network and Survey Support

Project Element B.3 provides the geodetic framework needed to enable high-accuracy change detection and to ensure that geospatial data collected in Project B and other projects are accurately referenced, precisely defined, and can be reliably compared with past and future data sets.

Positions for all spatial data products rely on a network of survey control measurements, which currently includes 9323 GNSS vectors and 8909 classical survey measurements. The network includes the base positions for nearly 500 individual multibeam sonar surveys of river channel bathymetry. The least-squares adjustment results and assessments from independent computations show 95% of stations have absolute and relative accuracies of 5 cm or better (at 2σ/ 95% confidence) throughout the study area. The network results are consistent with alternate processing and adjustment methods (e.g., AUSPOS, OPUS Projects) within < 5 cm (at 2σ/ 95% confidence), providing reassurances that the base maps we have created and the physical changes we measure are both reliable and repeatable.

GCMRC continues to work alongside the National Geodetic Survey to ensure the decades of spatial data collected within the Grand Canyon region can be seamlessly combined with future data sets. The North American Datum of 1983 (NAD83) will be superseded with the North American Terrestrial Reference Frame of 2022 (NATRF2022) in FY 2024. The U.S Geological Survey is well prepared for migration to the North American Terrestrial Reference System, and future spatial data collection will occur in newly developed coordinate systems: AZ GC (041017), AZ GC1 (042009), AZ GC2 (042010), AZ GC3 (042011), AZ GC4 (042012). These projections have been specifically designed for the region and are available to the public: https://noaa.maps.arcgis.com/apps/mapviewer/index.html?webmap=bf6e96dd1c954606b36121414cf33bcf

Element B.5. Streamflow and Fine Sediment Modeling

The purpose of this Project Element is to develop models for predicting the concentration and transport of silt- and clay-size sediment. Existing models in use by GCMRC and the Bureau of Reclamation focus on predicting sand concentration, sand transport, and sandbar deposition and erosion. Although silt and clay typically account for 60% or more of the total sediment input and suspended-sediment load on the Colorado River in Grand Canyon, very little effort has been directed at modeling this component of the sediment load because most of the bed and eddy sandbars are composed of sand-sized sediment. The silt- and clay-size sediment, however, strongly affects turbidity, which is increasingly recognized as a potentially important control on native and nonnative fish populations (Deemer and others, 2022; Ward and others, 2016).

This year we continued work on developing a new fine sediment (sand, silt, and clay) routing model, which includes sediment advection, eddy exchange, exchange with the bed, and storage/release from bar deposits. We are using extensive data sets collected over the past two decades to provide model inputs and for validation/calibration. The model has been improved over the last year to better include storage and release of mud and sand associated with bed and bar exchange, and preliminary results show that improvements to treating sandbar erosion in the model lead to better comparison with data. Additionally, this year we processed 24 new subaqueous bar sediment samples collected for this project that will improve model calibration.

This work presented at two conferences in 2023, at the Federal Interagency Sedimentation and Hydrologic Modeling Conference (SEDHYD), and River, Coastal, and Estuarine Morphodynamics Conference (RCEM), with corresponding published conference proceedings.

As part of this project, we have also supported the Bureau of Reclamation by running the Sand Routing Model (Wright and others, 2010) and Sandbar Model (Mueller and others, 2021) for a variety of applications. We provided modeling to support the fall and spring HFE implementation process using the Sand Routing Model. We have also provided modeling results for a number of environmental compliance documents, including the Smallmouth Bass EA, the LTEMP SEIS, the Interim Guidelines SEIS, and Post-2026 Planning. To accomplish this work, we developed scripts to automatically select the appropriate HFE durations and modify hydrographs to include them, across hundreds of possible hydrologic and sediment traces, and then compute sand export and sandbar building using the models referenced above.

We have made modifications to the Mueller and others (2021) sandbar model to improve its utility in predicting sandbar response to a range of conditions, particularly by expanding the data set used for calibration, and including a discharge-dependent erosion rule. The improved sandbar model is being used in ongoing work to assess how different strategies for operating Glen Canyon Dam and managing reservoir storage in Lakes Powell and Mead could improve sediment management and other environmental resources, for instance, by finding operational rules that mitigate the need to release a large volume of water over a short period of time due to changes in hydrologic forecasts, as occurred in summer 2023.

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Project B Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$391,856	$4,500	$30,200	$393,512	$0	$65,650	**$885,718**
Actual Spent	$578,659	$11,450	$163,580	$8,000	$0	$95,378	**$857,067**
(Over)/Under Budget	**($186,803)**	**($6,950)**	**($133,380)**	**$385,512**	**$0**	**($29,728)**	**$28,651**

COMMENTS

FY23 Comments:
-Overspent Salaries is due to bringing staff on as USGS employees instead of contracting with Northern Arizona University.
-Overspent Travel & Training is due to more staff at GCMRC and expenses moved from the cooperaive agreement to internal.
-Overspent Operating Expenses is due to purchased equipment for bathymetric surveys, using funds saved from not needing to do the cooperative agreemnt.
-Underspent funds in Cooperative Agreements is due to personnel working on this project having left Northern Arizona University and the agreement is not continued.

Project B Deliverables: Sandbar and Sediment Storage Monitoring and Research

Presentations:

Chapman, K.A., Grams, P.E., and Kaplinski, M.A., 2023, Effect of HFE frequency and dam Releases on sandbar deposition and erosion—presentation: Glen Canyon Dam Adaptive Management Program Meeting, Phoenix, Ariz., January 24-25, 2023.

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Web Applications:

Grand Canyon River Guides Adopt-a-Beach Photographs: http://www.gcmrc.gov/sandbar (https://grandcanyon.usgs.gov/gisapps/adopt-a-beach/index.html)

Remote Camera Sandbar Photographs: http://www.gcmrc.gov/sandbar (https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html)

Sandbar Monitoring Data: http://www.gcmrc.gov/sandbar (https://www.usgs.gov/apps/sandbar/)

Project C: Riparian Vegetation Monitoring and Research

Project Lead	Emily Palmquist	**Principal Investigator(s)** (PI)	Emily Palmquist, USGS, GCMRC Brad Butterfield, NAU
Email	epalmquist@usgs.gov		
Telephone	(928) 556-7397		

Goals and Objectives

This project aims to monitor changes to riparian vegetation using field-collected data (C.1), develop process-based models of vegetation responses to hydrological regimes through controlled experiments (C.2), develop predictive models of vegetation responses to hydrological and climate variability through synthesis of previous work across multiple hierarchical scales (C.3), and provide monitoring protocols and decision support tools for active vegetation management (C.4).

The list of accomplishments and products below is for fiscal year (FY) 2023. Products completed during this time frame are included in the "Deliverables" section. Results of both completed and on-going work initiated in FY 2023 are described in "Project Elements."

Project Elements

Element C.1. Ground-based Riparian Vegetation Monitoring

Science Questions

- 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 historical high-water line of Lake Mead, approximately 240 river miles downstream of Lees Ferry?
- How do dam operations interact with the physical and biological environment to determine vegetation status?

Results

Riparian vegetation monitoring data were collected at the long-term monitoring sandbars included in Project B and at randomly selected sandbars, debris fans, and channel margins in August-October 2023. Between River Miles (RM) -15.5 and 240, 99 randomly selected sites and 45 long-term monitoring sites were sampled. Data from 2023 are currently being entered into the riparian vegetation database and error checked. A summary of the status and trends in riparian plant communities based on annual monitoring data from 2014 through 2019 was published (Palmquist and others, 2023).

This report summarizes the composition and cover of plant species recorded during this time frame in Glen, Marble, and Grand Canyons and gives special consideration to hydrologic position, geomorphic features, and local climate. It also presents results on temporal trends in species richness, total foliar cover, proportion of native to nonnative species richness, proportion of native to nonnative species cover, saltcedar (*Tamarix*) cover, arrowweed (*Pluchea sericea*) cover, and species in the genus *Baccharis* combined (seepwillow, desertbroom, and Emory's baccharis) cover.

The analyses of species composition illustrated that long-term monitoring sites differ floristically from randomly selected sites, Glen Canyon (RM -15.5 to 0) is a unique floristic region, and plant communities regularly inundated by dam operations are significantly different from those rarely inundated. Overall, native species cover and richness were greater than nonnative species cover and richness. Species composition did not change over the monitoring period, but *Baccharis* species cover steadily increased in areas that experience daily water fluctuations.

The report discusses these findings in detail, as well as the utility of the metrics presented for tracking the status and trends of plant communities over time. The metrics currently under consideration for a larger, ongoing metrics development project (Chapter 1 C.12 in U.S. Department of the Interior, 2020) are included in this report for 2014 through 2019 (total plant cover, native plant richness, and native to nonnative species cover ratio). Data from this work were released in 2022 (Palmquist and others, 2022). The next status and trends report will summarize data through 2024.

Using monitoring data from 2016 through 2020, a study was conducted to determine how dam operations interact with air temperature variation and environmental context to influence plant populations downstream of Glen Canyon Dam. This builds on previous work seeking to understand the joint effects of dam operations and climate on riparian plant communities (Butterfield and others, 2018), but uses a full suite of environmental variables and a statistical analysis that examines both plant occurrence and cover. Specifically, presence and cover data for thirty-six plant species were analyzed with environmental and biotic variables using an ordinal, zero-augmented Bayesian model.

This model simultaneously analyzes presence and cover responses of each species with respect to temperature, hydrology, substrate, site conditions, and their interactions with mean annual temperature. A subset of these analyses is included as a chapter of a doctoral dissertation (Palmquist, 2022). Eight species representing native and nonnative forbs, grasses, shrubs, and a tree were presented – red brome (*Bromus rubens*, nonnative grass), horsetail (*Equisetum* x *ferrissii,* native forb), common reed (*Phragmites australis,* native grass), tall fescue (*Schedonorus arundinaceus,* nonnative grass), Emory's baccharis (*Baccharis emoryi*, native shrub), desertbroom (*Baccharis sarothroides*, native shrub), coyote willow (*Salix exigua,* native shrub), and saltcedar (*Tamarix ramosissima* x *chinensis*, nonnative tree).

The main findings from this work are well illustrated by desertbroom (*B. sarothroides*). This species presence and cover responses to the timing of daily tides, overhanging living plants, and channel width are modified by hotter temperatures (Figure C1, Interaction panel). It also occurs less frequently but has greater cover where daily tides are high during the day (Figure C1, Mean Midday CMS in Main Effect panel). Silts, clays, and sand are significantly positively related to desertbroom occurrence and cover (Fines and Sand variables, Main Effect panel). Finally, variables significantly correlated with species occurrence (Figure C1, Absence column) differ somewhat from those significantly correlated with species cover (Cover column). Taken together, these types of results can help to predict how species respond individually to dam operations, and that the responses of this (and many other) species to dam operations depends on climate and vice versa. One implication of this finding is that even if dam operations remain constant, species responses to those operations will change as temperatures increase.

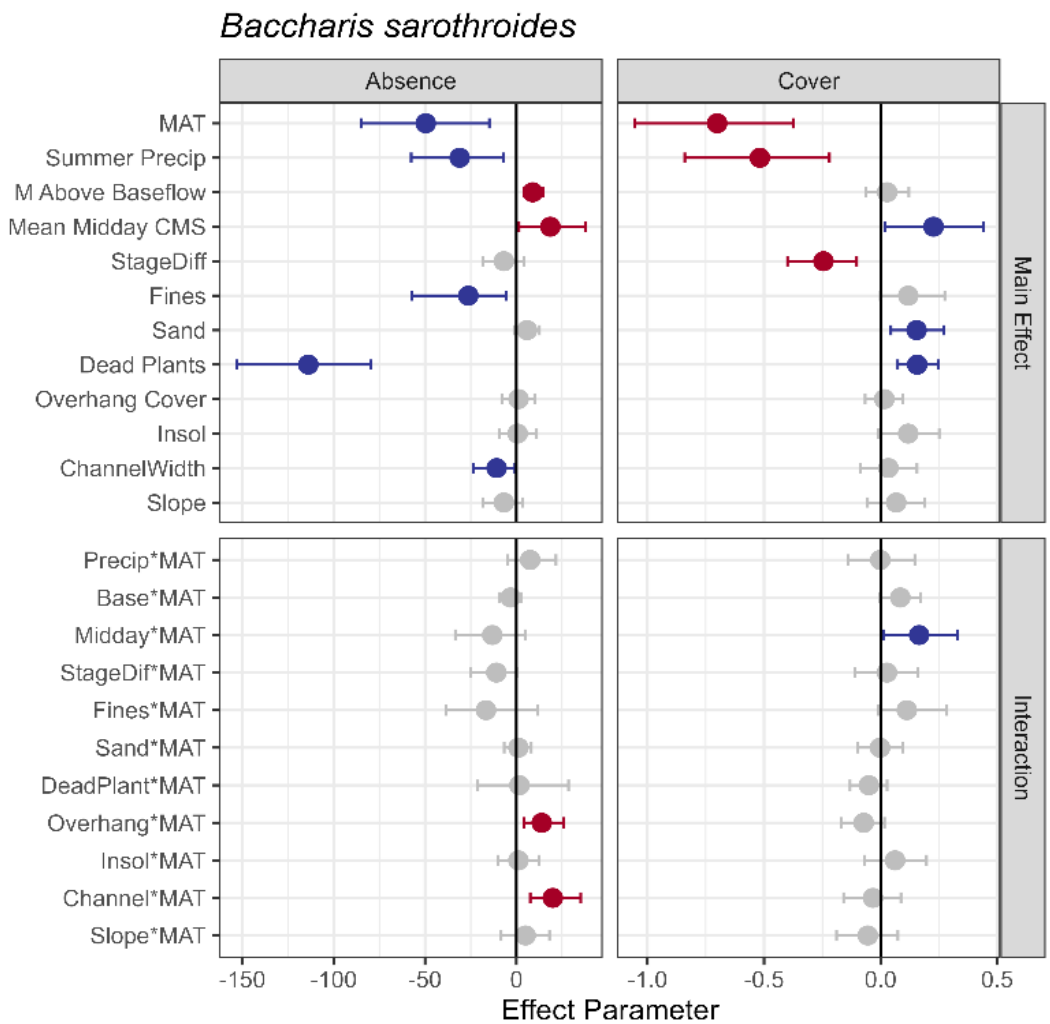

Figure C1. Summary of posterior parameter estimates for desertbroom (*Baccharis sarothroides*). Parameter estimates are shown for the presence/absence model (Absence) and the cover model (Cover). Significant covariate effects (credible intervals do not cross zero) that promote species success are in blue, while those that reduce species success are in red. Nonsignificant covariate effects (credible intervals cross zero) are in gray. Covariate abbreviations are MAT = mean annual temperature, Summer Precip = summer precipitation, M Above Base flow = meters above minimum flows, Mean Midday CMS = mean discharge in the afternoon, StageDiff = stage difference between low and high discharge, Fines = percent cover of silts and clays, Sand = percent cover of sand, Dead Plants = percent cover of dead plant material, Overhang Cover = percent cover of living, overhanging plants, Insol = solar insolation, ChannelWidth = channel width, Slope = site slope. Interactions between explanatory variables and mean annual temperature are noted by "*variable**MAT."

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

Science Questions

- How do plant species vary in their adaptations to seasonal variations in base flows versus daily fluctuating flows?

- How can a mechanistic understanding of plant physiological responses to dam operations improve vegetation management outcomes?

Results

Over the last three years, we've used a series of field and greenhouse experiments combined with an empirical model (Butterfield and others, 2023) to address the first question of this element. We leveraged the 2021 experimental spring disturbance flow (see Project O for more details) to evaluate physiological responses of arrowweed (*Pluchea sericea*) and tall fescue (*Schedonorus arundinaceus*) in the field (Butterfield and Palmquist, 2023). Results from this study indicated that the two species had differing responses to low and high flows. Tall fescue exhibited patterns consistent with sensitivity to low flows. Arrowweed exhibited patterns consistent with protection from drying conditions and capitalizing on short term water availability. From a management perspective, these results demonstrate that species respond asymmetrically to low versus high flow anomalies, and that the responses of individual species may be predictable based on differences in their functional strategies.

We conducted two greenhouse experiments, one in 2022 and one in 2023, to parse physiological responses to progressive inundation and drying, and daily water fluctuations, respectively (Butterfield and Palmquist, 2024). The first experiment utilized twelve plant species representing common and uncommon species downstream of Glen Canyon. Water levels were decreased, increased, or maintained at constant levels and root growth and stomatal conductance measured. These physiological responses were then compared to observed hydrological niches in the field. The results suggest that plant distributions in the field are largely determined by plant inundation tolerance rather than tolerance of drying. Additionally, Goodding's willow (*Salix gooddingii*) and Fremont cottonwood (*Populus fremontii*), both uncommon downstream of Glen Canyon Dam, exhibited consistently negative responses to both drought and inundation relative to species commonly occurring in the same study area.

The experiment conducted in 2023 evaluated species responses to daily fluctuating levels of inundation. Three species were included – Goodding's willow (*Salix gooddingii*), arrowweed (*Pluchea sericea*), and Emory's baccharis (*Baccharis emoryi*). The first species is uncommon downstream of Glen Canyon Dam, while the other two species have remained abundant or are increasing (Durning and others, 2021; Palmquist and others, 2023a). The experimental treatments consisted of a high tide during the day, a high tide during the night, and constant water levels (Figure C2). These were further divided into a low and a high level of inundation, such that the high tides either inundated all below ground parts of the plant or rose to the bottom of the roots. This design tested how these species responded to inundation during the day or night and non-inundating watering during the day and night versus constant inundation or constant non-inundating available water. We measured stomatal conductance, root growth, and stem water potential to evaluate physiological responses.

Results from this study will provide insight into species responses to daily fluctuating flows. Data from this study are currently being analyzed.

Inclusion of species that are used in restoration, but are uncommon along the Colorado River in Glen, Marble, and Grand Canyons, can provide insight into restoration outcomes. Both Goodding's willow (*Salix gooddingii*) and Fremont cottonwood (*Populus fremontii*) have been used in restoration projects but have had mixed rates of survival. The 2022 experiment (Butterfield and Palmquist, *in press-b*) suggests that these two species are more sensitive to variable hydrological conditions, such as changing monthly volumes, than species that are successful in this study area. This result indicates that planting efforts of these species will likely be more successful if restoration areas are in parts of the river that experience smaller differences in stage change, like wider parts of the river, and if plants are placed closer to minimum flows. This would minimize the hydrological variability for these planted individuals.

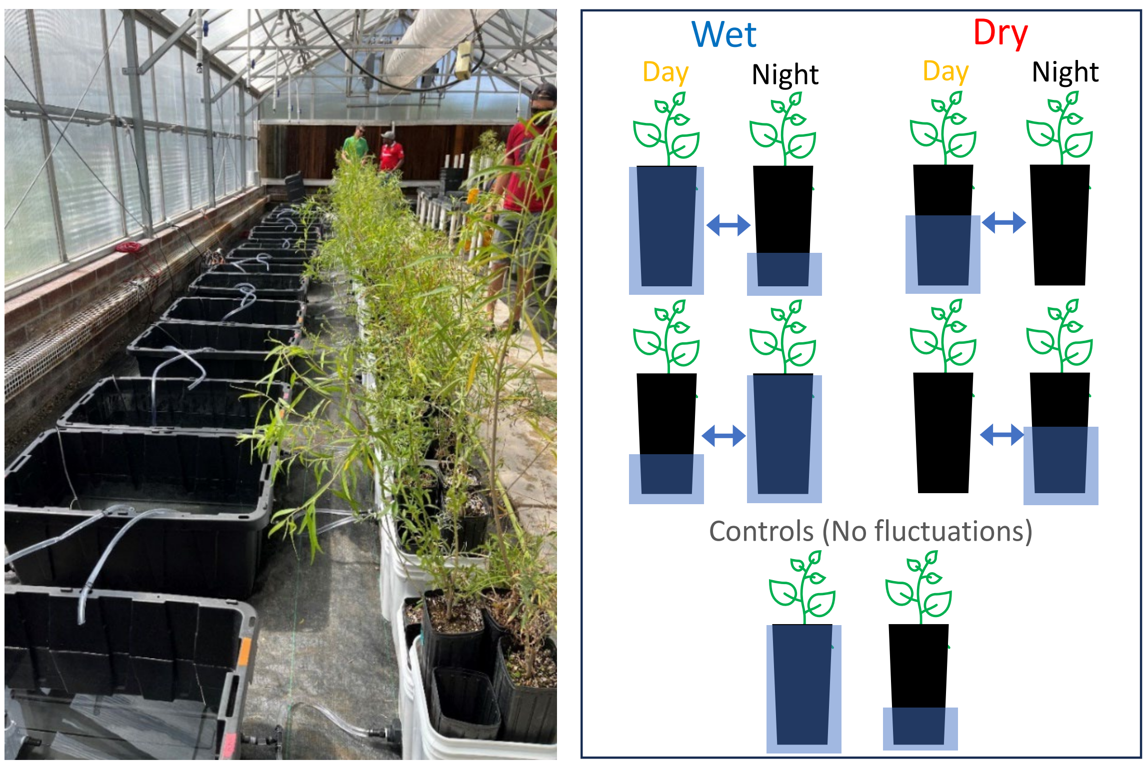

Figure C2. Experimental set up of the 2023 daily tide timing experiment. Left – picture of the experimental set-up that was established at the NAU Research Greenhouse Complex. Right – Diagram of treatments included in the experiment. Treatment bins were assigned to one of three water treatments: daily fluctuating flows that rise during the day, daily fluctuating flows that rise during the night, or steady inundation levels. Each treatment was further split into two levels – a higher inundation level and lower inundation level. See text for more details.

Element C.3. Predictive Models and Synthesis

Science Questions

- What are the predicted changes to Colorado River ecosystem (CRe) vegetation status in the future under current and alternative LTEMP dam operations?
- What are the knowledge gaps in CRe plant ecology, and how can we fill them with existing data sources?

Results

Building off of previous research (Butterfield and others, 2018; Butterfield and others, 2023), predicted species responses to alternative dam operations were generated in support of the Near-term Colorado River Operations Supplemental Environmental Impact Statement (SEIS) and the LTEMP SEIS. We conducted hydrological niche modeling of 47 common riparian plant species (33 native, 14 nonnative) growing on sandbars between Glen Canyon Dam and the confluence of the Colorado River with Diamond Creek, Arizona. Models were trained on extensive monitoring data and projected for each species for the No Action and three Federal Alternative scenarios, including multiple traces with 80, 90 and 100% of the Ensemble Streamflow Predictions (ESPs).

We also contrasted scenarios of Federal Alternative 3 that have High-Flow Experiments (HFEs) to No Action without HFEs, focusing on the 80% ESP and subdividing by traces from worst to best case scenarios with respect to lake levels. Proportion of native cover, total species richness, total vegetation cover, and several species of interest were chosen for metrics. Predicted effects of losing HFEs under No Action has at least an order of magnitude greater impact on vegetation resources than the redistribution of flows throughout the year. A formal report of these results is in progress and is expected to be published as a USGS Open-File Report.

We also provided a high throughput version of the niche modeling framework developed for the SEIS to the Bureau of Reclamation for inclusion in their web tool. Specifically, the niche models for the representative 47 species used in the SEIS were projected under a simplified range of environmental variation observed within the CRe to provide rapid throughput of the thousands of flow scenarios required by the web tool. This version allows stakeholders to see a range of predicted outcomes for three metrics (native species dominance, plant community diversity, and total vegetation cover) under any set of flow scenarios selected by the user. Many other resources are also modeled in the tool, so changes to plant communities can be constrasted with changes in other resources under different flow scenarios.

Element C.4. Vegetation Management Decision Support

Science Questions

- How can GCMRC monitoring and research be leveraged to assist with experimental vegetation management plans and implementation by the National Park Service (NPS) and Tribes?

Results

As in previous years, we participated in planning meetings for NPS-led non-flow experimental vegetation treatments (Reclamation Triennial Work Plan C.7 and C.8) to consult on ongoing removals and new work sites. Five campsites and a GLCA restoration site that are undergoing annual vegetation removal and maintenance are monitored annually as part of the collaborative GCMRC annual sandbar monitoring, which includes topographic, campsite (Project B) and vegetation (Project C) surveys: -6.6R, Basalt Camp, upper Clear Creek Camp, Granite Camp, 122 Mile Camp, and 202 Mile Camp.

Additionally, both PIs are serving on the Ph.D. committee of a Northern Arizona University student identified to work on the non-flow experimental vegetation treatments mentioned above. The overall theme of this student's research is evaluating the outcomes of these vegetation treatments. This research will include projects that grew out of our discussions with NPS about alternative vegetation removal methods.

A journal article describing the results of our greenhouse experiment testing the influence of inundation on arrowweed (*Pluchea sericea*) was published (Palmquist and others, 2023b). This work indicated that arrowweed growth is strongly related to inundation. It also showed that some genotypes of this species grow larger and faster than others and these genotypes are associated with parts of the Grand Canyon that have experienced greater arrowweed encroachment. In clonal species like arrowweed, aggressive and well-adapted genotypes can dominate landscapes. It is unclear if recent regional expansion of this species is partially related to expansion of a few genotypes in combination with changing environmental conditions. This study also illustrated that knowledge gleaned from studies on riparian trees is not applicable to the riparian shrubs that dominate the Colorado River in Glen, Marble, and Grand Canyons. Thus, shrub-specific research is necessary to understand the drivers of species expansion in this study area.

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Project C Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$136,566	$3,240	$3,310	$100,257	$0	$21,073	**$264,446**
Actual Spent	$125,031	$2,747	$5,910	$102,213	$0	$19,942	**$255,842**
(Over)/Under Budget	**$11,535**	**$493**	**($2,600)**	**($1,956)**	**$0**	**$1,131**	**$8,604**

COMMENTS
FY23 Comments: -Underspent Salaries is due to ongoing issues with technician hiring. -Underspent Travel & Training were to compensate for increased botanist costs. -Overspent funds in Operating Expenses were due to contracting a boatman since planned in-house boatmen were unavailable. -Overspent funds in Cooperative Agreements was due to increased costs for hiring botanists through NPS.

Project C Deliverables: Riparian Vegetation Monitoring and Research

Presentations:

Butterfield, B., and Palmquist, E.C., 2023, Predictive vegetation modeling: Progress and opportunities for growth—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

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USGS Data Releases:

Palmquist, E.C., Butterfield, B.J., and Allan, G.J., 2022, Arrowweed (*Pluchea sericea*) morphological and physiological response data from a greenhouse inundation experiment: U.S. Geological Survey data release, https://doi.org/10.5066/P9412RYV.

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

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC Helen Fairley, USGS, GCMRC
Email	jsankey@usgs.gov		
Telephone	(928) 556-7289		

Goals and Objectives

The LTEMP 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.

Project D quantifies changes in the physical condition of river corridor archaeological sites in Grand Canyon as a function of: 1) dam operations, 2) vegetation management, and 3) natural processes. While the dam and its operation are not the only sources of change affecting the Colorado River ecosystem (CRe) and associated archaeological sites, this project focuses on studying and monitoring dam effects, in keeping with the mandates of the Grand Canyon Protection Act (GCPA) and consistent with the monitoring plan developed in 2015 and Reclamation's 2017 Historic Preservation Plan. The ongoing and experimental dam operations and vegetation management actions of interest are those that are undertaken under the Record of Decision for the Glen Canyon Dam (GCD) Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP ROD; U.S. Department of the Interior, 2016b) through 2036.

Here, we report on progress made during FY 2023 on monitoring the effects of dam operations and vegetation management at archaeological sites under the different elements of this project. The project consists of four elements, but we only report on the two elements (D.1 and D.2) that were funded in FY 2023, as well as additional work completed in FY 2023 to address new science questions following stakeholder requests.

Element D.1 focuses on the effects of dam operations, including High-Flow Experiments (HFEs), on the supply of sediment to cultural sites. It also examines the effects of vegetation management implemented by the NPS and Tribes in Bureau of Reclamation Project C.7-C.8 GRCA and GLCA Experimental Vegetation Treatment. The data and analyses from D.1 allow the GCD Adaptive Management Program (AMP) to objectively evaluate whether and how these flow and non-flow actions directly affect cultural resource condition in relation to vegetation and sediment dynamics.

They will also allow determination of how flow and non-flow actions will ultimately affect the long-term preservation of cultural resources and other culturally valued and ecologically important landscape elements located within the river corridor downstream of GCD. Element D.2 uses repeat photography methods and an analysis of matched images to document changes in riparian cover at locations throughout the CRe. The purpose of documenting these changes is to refine our current understanding of how vegetation growth and expansion has evolved and affected the availability of open sand sources, which in turn, have had consequences for cultural resource preservation throughout the CRe.

Project Elements

Element D.1. Geomorphic Effects of Dam Operations and Vegetation Management

Science Questions/Hypotheses Addressed

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

Results

Monitoring the effects of flow and non-flow actions on archaeological resources within Grand Canyon's Colorado River Corridor (CRC) focused on two primary sources of data: 1) detailed measurements of topographic change from repeat ground-based lidar surveys at a small subset (n=31) of archaeological sites distributed across the CRC and 2) observed changes in geomorphic condition at a larger population (n=362) of sites. Monitoring by ground-based lidar began in 2006 to specifically address LTEMP requirements (Collins and others, 2008; 2009; 2012; 2014), and these efforts have expanded since, with the largest number of new and repeated monitoring surveys conducted during the extended Triennial Work Plan (Figure D1).

By having repeat topographic surveys that span flow actions, like the 2016, 2018, and 2023 HFEs, and non-flow actions, like the NPS vegetation management efforts in 2019 – 2023, related geomorphic changes can be measured as topographic change to quantify their effect. Caster and others (2022) reported measured topographic changes for 13 sites with at least one repeat survey between 2010 and 2020. The reported results agree with previous conclusions by Sankey and others (2018b) that HFEs can help reduce net erosion at archaeological sites outside of the active river channel where there is sandbar building and winds capable of transporting sediment from sandbars to archaeological sites.

Geomorphic condition of CRC archaeological sites and their changes have been previously described by East and others (2016; 2017) using two categorical classifications for the larger population of 362 sites: 1) the “aeolian” classification is based on the transport of new sediment to cover an archaeological site and reduce weathering potential, where Type 1 has the best potential for new sediment and Types 2 – 5 have increasingly greater obstacles to sediment transport such as vegetation growth and loss of sandbar deposition, and 2) the “drainage” classification based on the maturity of the flow path, where Type 1 has no defined runoff pathway, and the largest number, Type 4, is a mature drainage path that has eroded down to the active river elevation. During FY 2023, Sankey and others (2023) reported updated classification results of each of the 362 CRC archaeological sites and synthesized the results with the topographic changes reported by Caster and others (2022). They found that sites with an aeolian Type 1 classification tended to have less negative (erosional) topographic changes than sites with obstacles to sediment transport from the river to the archaeological site, but the number of these Type 1 sites have continued to decrease throughout the CRC from the 1970s through the present (2023). Overall changes in both the aeolian and drainage classifications along with measured topographic changes by ground-based lidar suggest loss of preservation potential for archaeological sites owing to the long-term operations of the Glen Canyon Dam (Sankey and others, 2023). However, where active management has been conducted through vegetation removal efforts by the NPS, geomorphic condition appears less degraded and may provide another management tool that can help offset erosion.

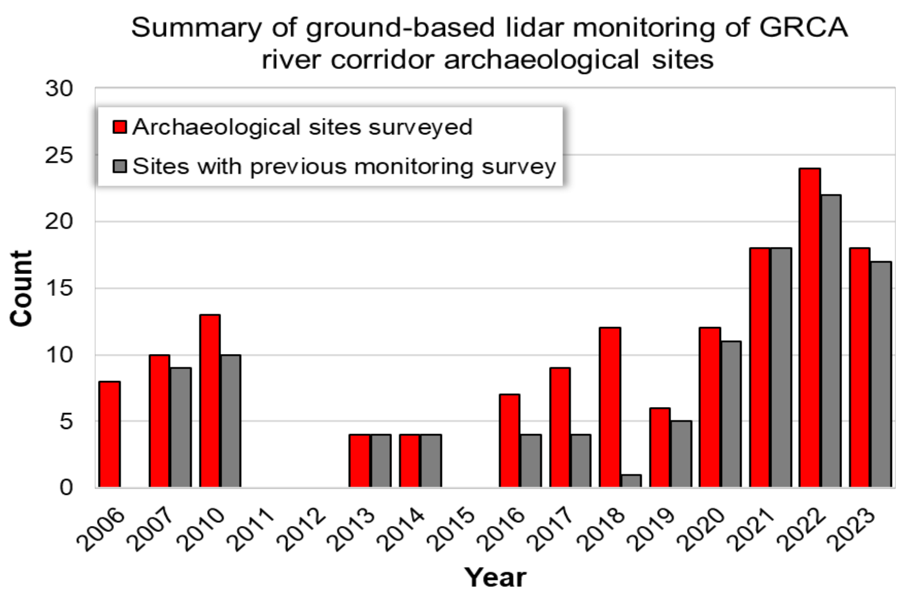

Figure D1. Bar graph showing the number of archaeological sites within the Grand Canyon National Park Colorado River Corridor (CRC) that were surveyed each year using ground-based lidar since 2006. Red bars represent the total number of sites surveyed each year and gray bars represent the number of those sites that were surveyed during at least one of the previous years (repeated surveys). Repeated surveys allow for detection of geomorphic changes within and around archaeological sites that are measured as topographic differences between the first and last survey.

The active management of vegetation removal by the NPS began in 2019 (Pilkington and others, 2021) and, until April of 2023, no HFEs had been conducted in conjunction with these non-flow actions. Monitoring of these efforts by GCMRC using ground-based lidar occurred at six locations over the past five years, showing that repeated annual vegetation removal by NPS staff appeared to have reduced overall invasive plant density and canopy height within the treatment area (see Figure D2 for an example of preliminary results from one site).

The reduction of vegetation within the management area permitted at least a portion of sediment trapped on river sandbars by vegetation to migrate downwind (Example Figure D2, panel D), providing habitat for native species of psammophytes, or sand-loving plants, such as dune broom (*Parryella filifolia*), Indian ricegrass (*Achnatherum hymenoides*), and sand dropseed (*Sporobolus cryptandrus*).

Beginning in 2022 and continuing in 2023, monitoring occurred at an additional location at Paria Beach, just downstream of River Mile (RM) 0 that incorporated vegetation removal as well as native tree restoration including Fremont cottonwoods (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*). Preliminary review of ground-based lidar monitoring at this site in 2023 documented significant wind-blown transport following invasive species removal as well as loss or establishment of transplanted saplings after restoration efforts. Specifically, bank erosion from river flows < 20,000 ft^3/s that overtopped the Paria Beach sandbar during 2022 resulted in loss of several saplings, though higher elevation transplants preliminarily appear to be established and retaining local sediment.

At lidar monitoring locations around RM 24.5 (river left) and RM 70 (river right), deposition occurred as shallow, flat deposits below the erosional scarps marking the maximum flow elevation shoreline (Example Figures D2 and D3). Downstream around RM 122, the sandbar and vegetation management area responded differently to the high flows, with the sandbar shoreline retreating meters inland (Example Figure D3, panel F).

Water surface elevations remained high after the HFE in May 2023 preventing evaluation of changes at RM 122 or other sites down to base flow conditions. Although deposition was noted below the water surface at RM 122, the portion of the sandbar that was subaerially exposed during the site survey in May 2023 had eroded measurably during the HFE or previous year, losing about one-fourth of the sediment area within the vegetation management area. Following the HFE, higher releases throughout the summer months between Glen Canyon Dam at Lake Powell and Lake Mead caused the shoreline of the newly formed sandbars to retreat at this location and others (Example Figure D3). However, incipient aeolian dunes still formed on the river sandbars and migrated inland through the vegetation management areas at some of the study areas (Example Figure D3, panel B and Figure D3, panel D).

These preliminary results demonstrate the complex and varied response of HFEs and subsequent dam operations at different reaches and sites throughout the CRC.

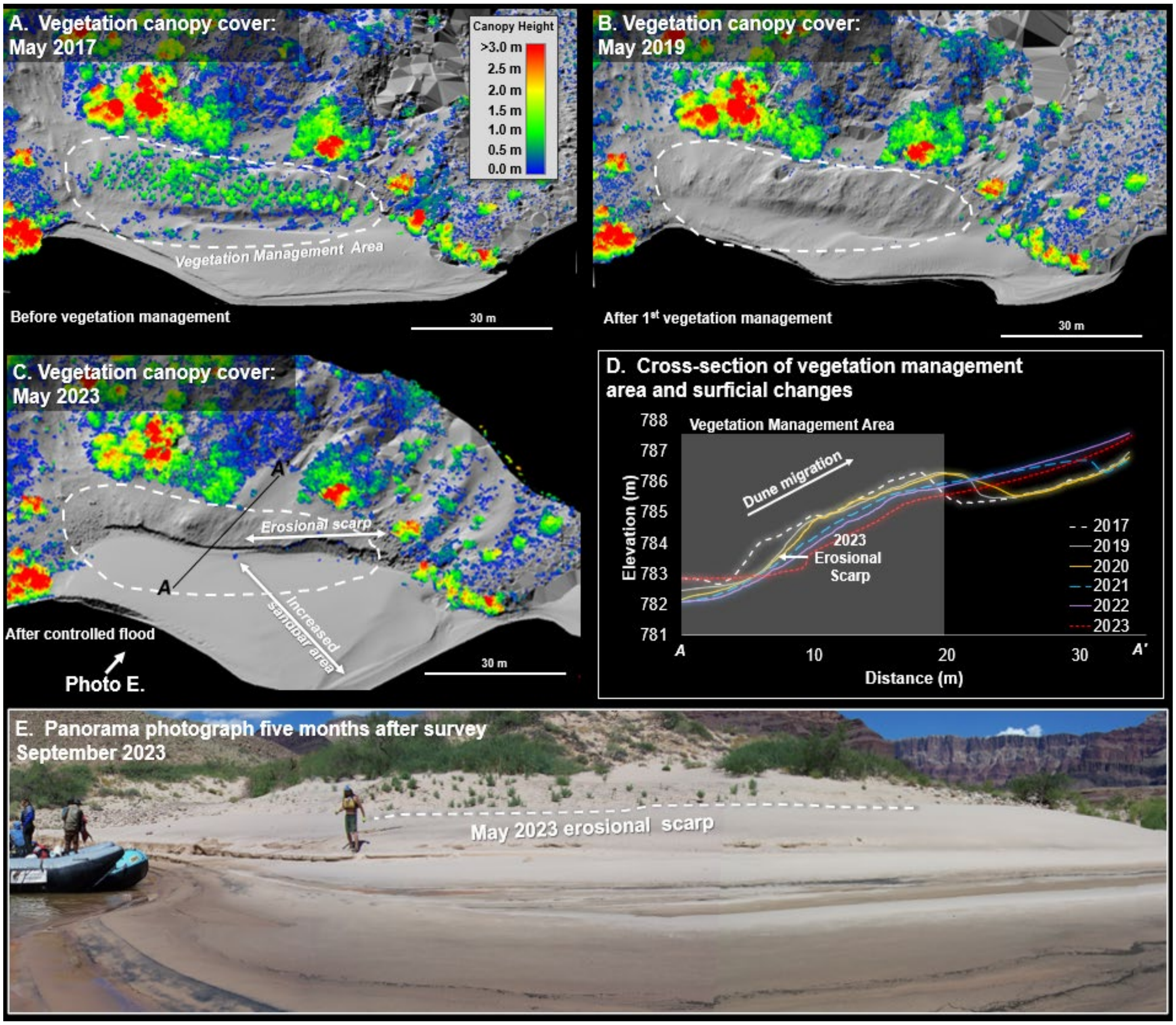

Figure D2. Example **t**opographic relief model and vegetation canopy height model produced from ground-based lidar at one monitoring location (RM 70R) with active vegetation management by National Park Service staff. **A**. Lidar data collected in May 2017 prior to vegetation management efforts showing dense arrowweed (*Pluchea sericea*) within the currently managed area (white dashed line). **B**. Lidar data collected in May 2019 within a month of vegetation management efforts. Note the near absence of vegetation within the management area. **C.** Lidar data collected in May 2023 less than a week after the April 2023 HFE and following multiple years of vegetation management. Note the large flat depositional bar below a steep erosional scarp within the management area. **D.** Plot of profile A-A' in Panel C showing data from all surveys collected between 2017 and 2023. Note the migration of the foredune upslope through 2022 and the erosional scarp at the HFE flow elevation shoreline and depositional bar below. **E.** Panorama photograph collected four months after the May 2023 lidar survey during the NPS vegetation monitoring trip. The approximate location of the erosional scarp in Panel C is provided for reference but is no longer visible because sediment transport by wind has built a new dune that is migrating upslope from the shoreline.. In panels A-C, and D, the direction of river flow is from the right side of the photo to the left side. Results shown in Panels A and B are published in Caster and others, 2022. Provisional data, subject to change.

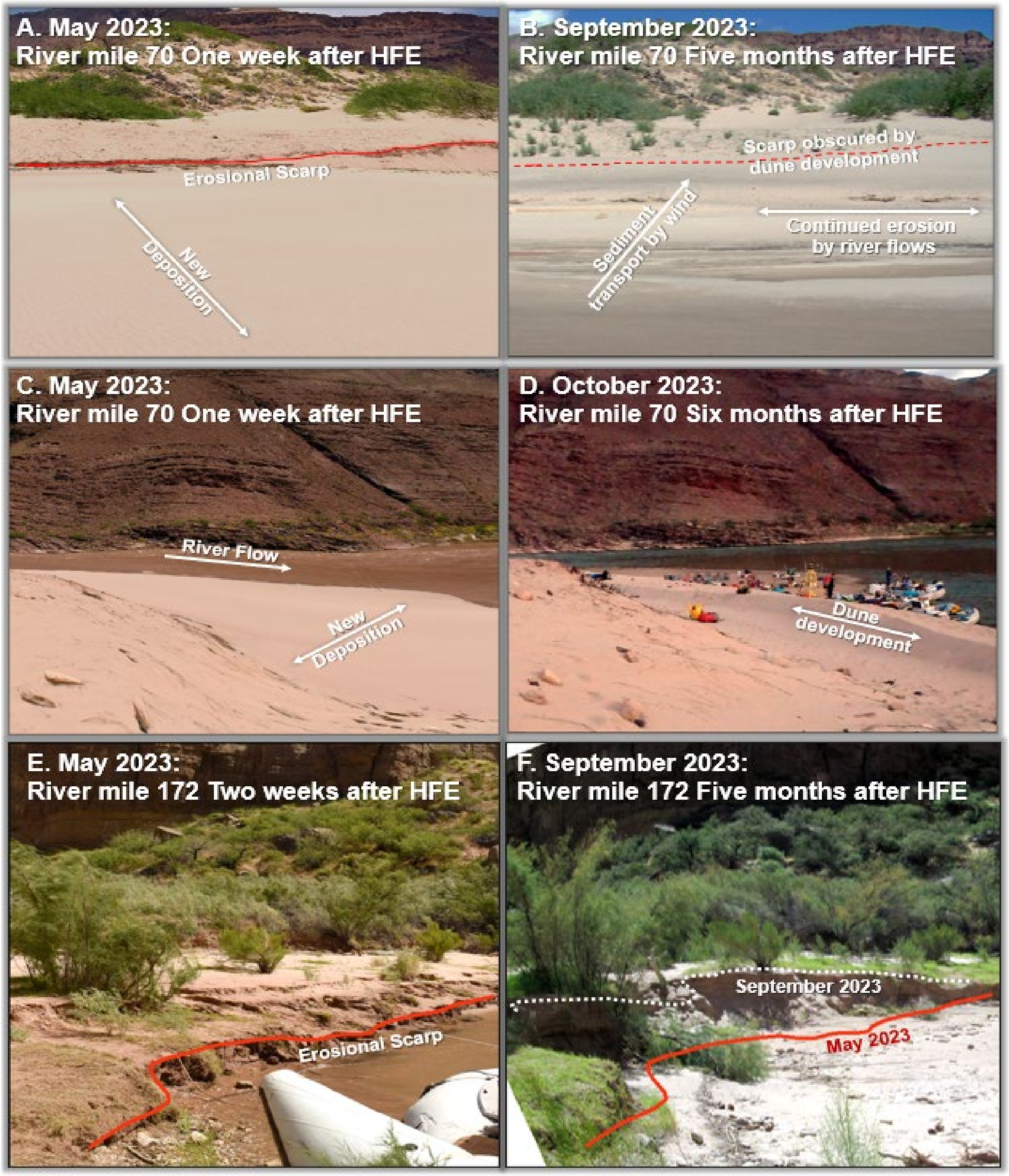

Figure D3. Photographs collected during ground-based lidar surveys at two vegetation monitoring locations compared with photographs collected at least five months later. Panels **A**-**D** were collected at Basalt Camp at RM 70 (river right). These photographs show new sand deposition on the relatively flat sandbar and an erosional scarp (red line) formed along the shoreline around the extent of the maximum flow during the April 2023 HFE. Within five months following the HFE, transport of sediment away from the active river channel by wind created a dune obscuring the erosional scarp. The dune is migrating toward the river camp, replenishing sand resources used by native plants, helping to reduce weathering potential from archaeological sites farther upslope through burial, and providing better conditions for recreational users within the designated camp. Panels **E** and **F** are photographs collected at Mohawk Camp around RM 172 (river left). Although a wide, flat section of sandbar was built below the water surface at this site, these photographs show a progression of bank erosion along the shoreline, with the May 2023 erosional scarp (solid red line) retreating a meter or more by September 2023 (dashed white line).

In addition to the vegetation management areas, monitored archaeological sites also appeared to respond to flow and non-flow actions as measured by topographic changes (Sankey and others, 2023). Reported topographic changes by Caster and others (2022) showed that new sediment deposition at archaeological sites was greatest between 2016 and 2019 when two HFE releases occurred (Fall 2016 and Fall 2018). After 2019, erosion became more prominent (Sankey and others, 2023; Caster and others, 2022), potentially as a consequence of the lack of new sandbar sediment deposition prior to the April 2023 HFE.

Although erosion was common without new sandbar deposition by HFEs, archaeological sites downwind of vegetation management areas continued to receive new sediment deposition and potentially eroded at a slower rate (for example Figure D4), in-part owing to wind-blown sediment that migrated toward archaeological sites. Specifically, between 2019 and 2021, three of the four sites within 50 m of the vegetation management area (Figure D4; AZ C:05:0031, AZ C:13:0321, AZ B:14:0105, AZ G:03:0072) either had positive topographic changes (deposition) or small negative changes (minor erosion).

The lidar and geomorphic classification data sets updated in FY 2023 were supplemented by on-site weather stations continuously monitoring meteorological data at six locations (RM 0, 11, 24.5, 70, 125, and 223.5) in the CRC (Caster and others, 2014; 2018). These data have been previously informative for this and other projects (for example, Caster and Sankey, 2016; Collins and others, 2016; Butterfield and others, 2018; Sankey and others, 2018a, b; 2022) and during FY 2023, these data were used to develop models to predict potential cultural resource impacts of future flow actions proposed within the SEIS and other pending Colorado River Basin water policy decision-making processes (for example, see FY 2023 modeling work described in the section at the end of Project D titled “Additional work in response to stakeholder requests not originally included in Project D Elements”).

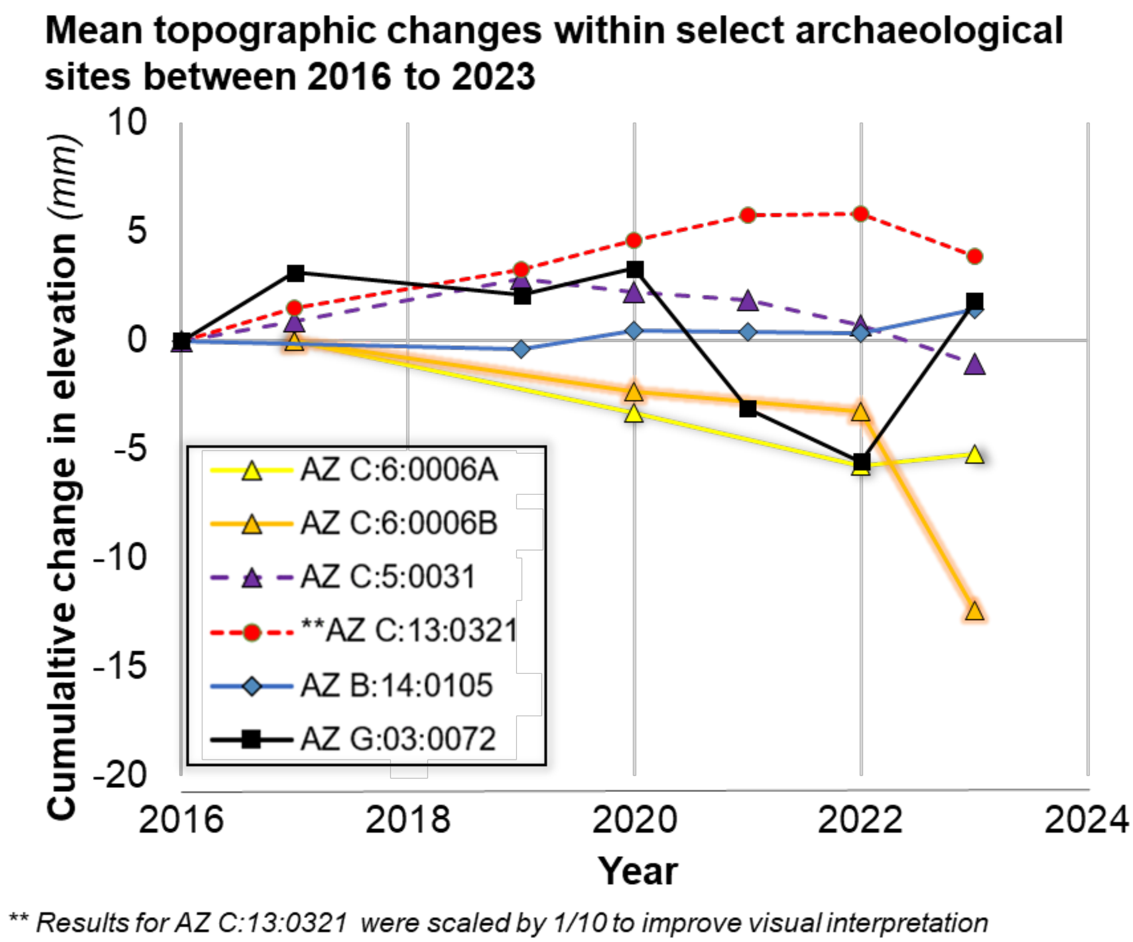

Figure D4. Example of geomorphic changes within monitored archaeological sites between 2016 and 2023 measured as area normalized elevation change (net topographic change volume divided by archaeological site area). The plot shows cumulative changes in elevation since 2016 at select sites in Marble, eastern, and western Grand Canyons with multiple repeat ground-based lidar surveys. Note that changes in elevation at site AZ C:13:0321 have been scaled by a factor of 1/10 to plot within the range of the other example sites. Each site is a Type 1 aeolian site following vegetation management implemented by the National Park Service in 2019 and annually thereafter; meaning that vegetation barriers have been reduced between the sandbar and downwind archaeological site, providing the best opportunity for transport of river-sourced sediment and reduction of weathering within the archaeological site. We note that each Type 1 archaeological site responded uniquely to natural and managed conditions, highlighting the complexity of responses throughout Grand Canyon. Results shown for 2016-2020 are published in Caster and others (2022). Provisional data, subject to change.

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

Science Questions/Hypotheses Addressed

- 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 the pre-dam period during drought

periods characterized by lower annual flows show more riparian cover compared with photographs taken during pre-dam periods characterized by wetter conditions and higher average annual flows?

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

Results

In FY 2023, we continued matching historical photographs with identical current views to document changes in riparian vegetation and geomorphic conditions, including changes to open sand areas that serve as source areas for aeolian sand, plus associated dune fields and shorelines. As in previous years, this photo-matching effort was conducted with the assistance of two unpaid volunteers, Dr. Michael Scott, retired USGS riparian ecologist, and Mr. Alan Fairley, retired lawyer and experienced amateur photographer.

In 2023, we matched a total of 63 historical photographs. As in 2021 and 2022, we focused primarily on matching color slide images of campsites originally photographed in 1973 (n=56). These campsites were initially photographed in conjunction with an NPS-sponsored campsite carrying capacity study (Borden and others, 1975; Weeden and others, 1975). In addition, we matched three photographs taken by E.C. La Rue in 1923, one by Emery Kolb also taken in 1923, two by Robert Brewster Stanton taken in 1890 and one photograph taken in 1872 by John Hillers on the second Powell expedition.

As described in previous Annual Reports, the 1973 images are particularly useful to match because they show the condition of campsites ten years after Glen Canyon Dam began regulating flows, when effects from dam operations on sediment and vegetation were starting to become evident but before substantial transformation of the riparian zone had occurred (Figure D5). Many of the campsites that were usable in 1973 are still used by boaters today, despite sediment loss from fluctuating flows, hillslope runoff and gullying, lack of sediment replenishment, and riparian vegetation encroachment (Hadley and others, 2018; Hazel and others, 2022) (Figure D5a-b); however, many other camps are no longer usable today due to significant vegetation encroachment and sediment loss (Figure D5c-d). Regardless of whether camps remain habitable or not, vegetation encroachment and the reduction of open sand areas is a common theme in almost all matched images. As in the past, the collection of matched images was accompanied by a detailed recording of the riparian vegetation visible within the photograph viewshed. The vegetation inventory is segregated into several “bins”: 1) new low water zone (ca. 8000-25,000 ft^3/s), 2) new highwater zone (ca. 25,000-45,000 ft^3/s), old highwater zone (45,000-120,000 ft^3/s), and the historical highwater zone (> 120,000 ft^3/s).

These bins correspond to inundation zones previously defined by Sankey and others (2015), as follows: Bin 1 = Zone 1, Bin 2 = Zones 2 and 3, Bin 3 = Zone 4 (up to 97,000 ft^3/s), and Bin 4 = ~Zone 5 (Bin 4 includes everything above 120,000 ft^3/s whereas Zone 5 is defined by Sankey and others, 2015 as the area between 97,000 and 210,000 ft^3/s). Analysis of changes within and between these bins is underway but not yet completed.

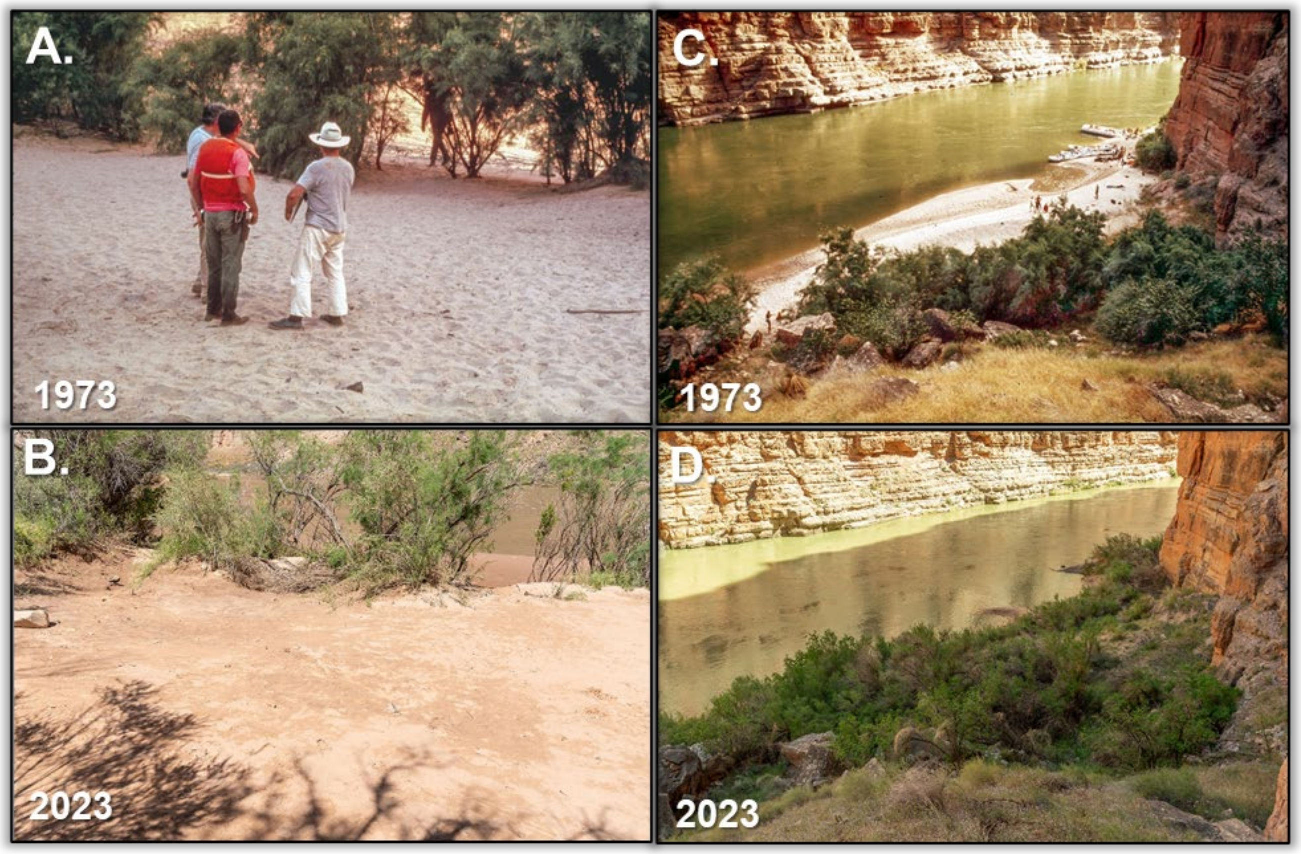

Figure D5. Two examples of campsites photographed by Borden-Weeden in July 1973 (top images, 5a left, 5c right) compared to their current condition (bottom images, 5b left, 5d right) in April 2023. Left photo match (5a-b) taken at RM 53.4, right bank, looking toward the river. This place is still a very popular campsite today. Note how sediment has built up in foreground, which is downwind of the row of Tamarisk trees and prevailing wind direction, while sand has been eroded and the bank has steepened toward the river. Right photo match (5c-d) at RM 38.6, left bank, looking upstream. This camp is no longer used by river runners due to significant vegetation encroachment. 1973 photographs (top images) taken by unnamed members of the Borden-Weeden study; 2023 photographs (bottom images) by A.H. Fairley, (5b) April 30, 2023, and (5d) April 29, 2023.

Additional work in response to stakeholder requests not originally included in Project D Elements

Science Questions/Hypotheses Addressed

- How will future alternative scenarios for the operation of Glen Canyon Dam considered in the Supplemental Environmental Impact Statement process potentially impact the preservation potential of cultural resources in Grand Canyon National Park? (*Addressed in FY 2023 at the request of Reclamation and the GCDAMP.*)

- Are dam operations or non-flow management actions influencing petroglyph site erosion and achieving the LTEMP resource goal of preservation in place? (*Addressed in FY 2023 at the request of members of the LTEMP Cultural Programmatic Agreement.*)

Results

In FY 2023, at the request of Reclamation and the GCDAMP, we conducted modeling to determine the area of exposed, dry river sand between Glen Canyon Dam and Bright Angel Creek within the CRe. This modeling was conducted as part of the Supplemental Environmental Impact Statement (SEIS) process and considers four alternative scenarios for the operation of Glen Canyon Dam, the "No Action" and the "Alternative 1," "Alternative 2," and “Alternative 3” scenarios. Cultural resource preservation potential in Grand Canyon National Park increases with larger values of exposed, dry Colorado River sand that is susceptible to windblown (aeolian) transport (Sankey and others, 2023).

The model (Kasprak and others, 2021) predicts the area of bare, dry sand for the upper ~103 miles of Grand Canyon between Glen Canyon Dam and Phantom Ranch/Bright Angel Creek. It uses a time series of daily maximum discharge from Glen Canyon Dam, field-derived maps of bare sand from a combination of multi- and single-beam sonar, total station, and aerial photo interpretation, in combination with hydraulic models of inundation extent to derive the total exposed bare sand area for a given discharge from Glen Canyon Dam. This initial bare sand area is modified to incorporate its exposure time, as longer exposure times result in progressively drier, and thus more transportable, sand. The development of the model was originally detailed in Kasprak and others (2021) and the modifications based on drying time follow Sankey and others (2022). Since the modeling was conducted for the SEIS, project staff have since worked to improve the model further for use in future efforts, such as the post-2026 process that will identify a range of alternatives and determine operations for Lakes Powell and Mead and other water management actions for coming decades.

In response to a request by the members of the LTEMP Cultural Programmatic Agreement, initiated by a representative of the Pueblo of Zuni and a GRCA archaeologist, we included a petroglyph panel, AZ C:06:0005, within our FY 2023 monitoring plan in addition to monitoring conducted for Project D. In 2016, USGS representatives in cooperation with NPS archaeologists visited the site and collected a series of photographs that were recently used to construct a three-dimensional photogrammetric model.

With the support of the cultural programmatic agreement team, repeat data were collected in April 2023 using ground-based lidar and photogrammetry to develop a baseline data set for evaluating potential past and future changes. The lidar baseline data set was collected at mm-resolution and provides sufficient detail to assess petroglyph characteristics, such as petroglyph shape and depth.

Although the methodology and level of detail were superior for baseline data collection in 2023, the 2016 photogrammetric model was of sufficient quality to assess approximately seven years of surface changes. Depth from the surface elevation around the exterior of each petroglyph to the interior surface of each petroglyph component did not appear to significantly change between 2016 and 2023; however, significant changes were measured adjacent to the petroglyph panel along an exfoliation joint (Figure D6). Although weathered and broken fragments observed in 2016 along the exfoliation joint (Figure D6, panel C) might be from natural weathering, we note that erosion along this joint could also be accelerated by site visitation.

The absence of the weathered material in 2023 suggests that visitors to the petroglyph may have intentionally or unintentionally removed rock fragments, or a heavy monsoon downpour might have caused surface runoff sufficient to remove the fragments. Although there is no evidence of direct river flow impacts since 2016, patterns of surface abrasion near the petroglyph panel suggest that the river could influence panel preservation at sustained high flows, such as were released in 1983 following emergency dam operations.

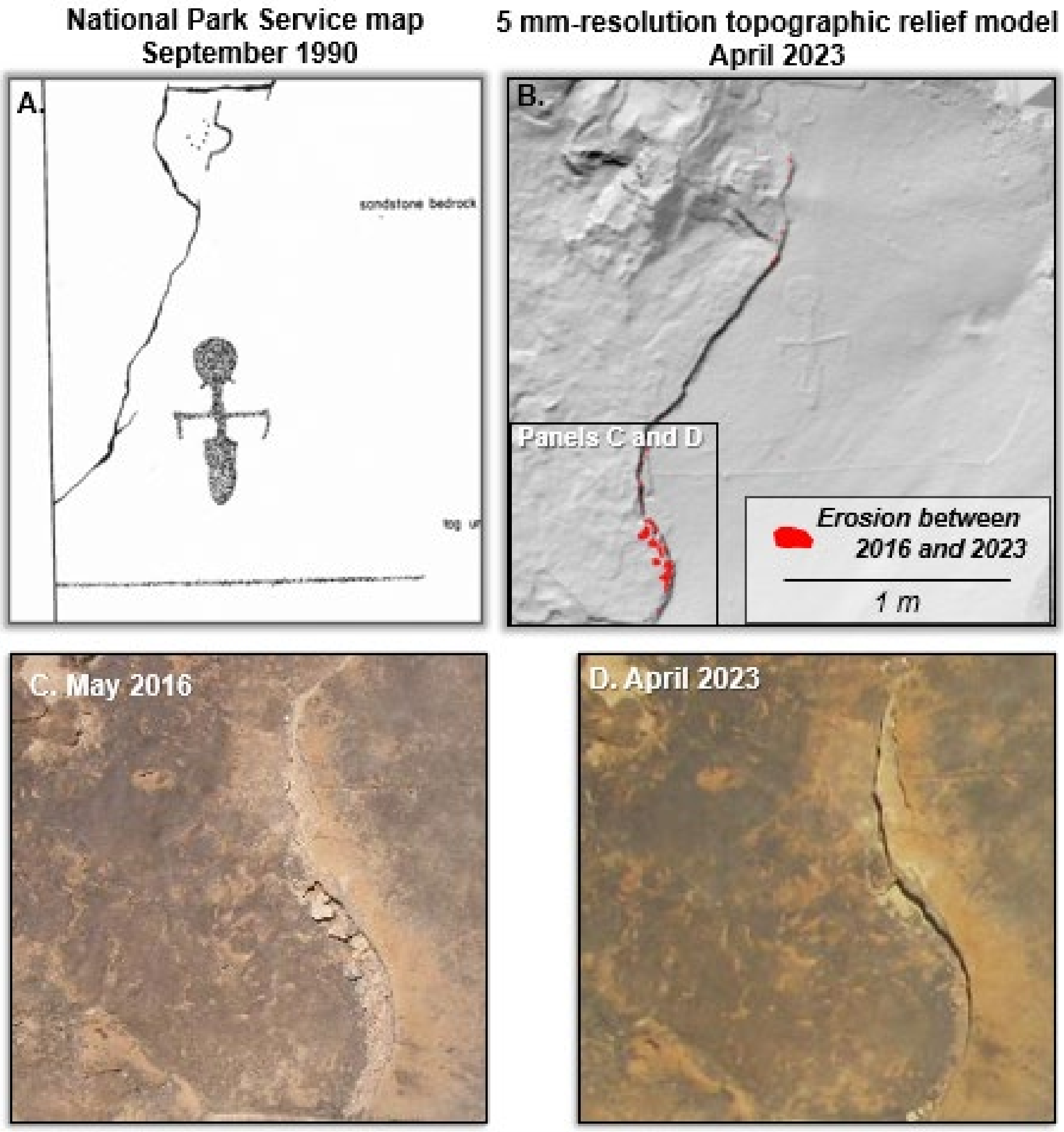

Figure D6. Map and photography of the petroglyph site C:06:0005 “Supai Man.” **A**. Site map drawn by T. Samples and A. Crew in September of 1990 as documentation for a National Park Service archaeological site form. **B**. Example 5-mm resolution topographic relief model developed from the mm-resolution ground-based lidar survey conducted in April 2023. Survey covered an area that was previously photographed in 2016 with sufficient detail to create a photogrammetric topographic model. Areas in red represent potential differences (erosion) between the 2016 and 2023 topographic models. Photographs collected in (**C**) May 2016 and (**D**) April 2023 showing the area of measured surface changes. Note the loss of material in 2023 that can be observed in the 2016 photograph along the edge of a natural exfoliation joint. Visitation at this site may accelerate erosion at this joint and may have resulted in removal of subsequent weathered material. Provisional data, subject to change.

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Project D Budget

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$204,799	$9,800	$3,223	$0	$0	$27,496	**$245,318**
Actual Spent	$199,686	$8,116	$9,938	$0	$0	$27,485	**$245,225**
(Over)/Under Budget	**$5,113**	**$1,684**	**($6,715)**	**$0**	**$0**	**$11**	**$93**

COMMENTS
FY23 Comments: - Underspent Salaries is due to short delay in hiring. - Underspent Travel & Training is due to postponed travel. - Overspent amount in Operating Expenses is due to increase in publication costs and equipment replacement needs.

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

Presentations:

Caster, J., Sankey, J.B., and Fairley, H., 2023, Monitoring for potential threats to Grand Canyon Rock Art—Preliminary observations and results at the Supai Man Petroglyph site—presentation: Long-term Experimental and Management Plan (LTEMP) Cultural Programmatic Agreement (PA) Meeting, October 2, 2023.

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Caster, J., Sankey, J.B., Sankey, T.T., Bowker, M.A., and Joyal, T., 2023, Effects of biocrust cover on potential dust emissions in an aeolian dunefield—abstract: International Conference of Aeolian Research, Las Cruces, NM, July 9-14, 2023.

Caster, J., Sankey, J.B., Sankey, T.T., Kasprak, A., Bowker, M.A., and Joyal, T., 2023, Relating geomorphic change by land cover to spatio-temporal trends in dune mobility within a partially-vegetated and sediment-starved dunefield—abstract: International Conference of Aeolian Research, Las Cruces, NM, July 9-14, 2023.

Fairley, H.C., Scott, M.L, and Fairley, A.H., 2023, Assessing 50 years of ecological changes at campsites along the Colorado River in Grand Canyon—Presentation: Glen Canyon Dam Adaptive Management Program Meeting, Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

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Sankey, J.B., Caster, J.J., Fairley, H., Pilkington, L., Dierker, J., and Brennan, E., 2023, Experimental vegetation management to improve the in-situ preservation of archaeological sites in aeolian dunefields along the Colorado River In Grand Canyon, USA—presentation abstract: International Conference of Aeolian Research (ICAR), Las Cruces, NM, July 9-14, 2023.

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Sankey, J.B., Fairley, H., Caster, J.J., Dierker, J., Brennan, E., Pilkington, L., Bransky, N., and Kasprak, A., 2023, Archaeological sites are eroding in Grand Canyon owing to six decades of Glen Canyon Dam Ooerations—Floods, low flows and vegetation management can help—presentation: Long-term Experimental and Management Plan (LTEMP) Cultural Programmatic Agreement (PA) Meeting, Phoenix, Ariz., April 11, 2023.

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Caster, J., Sankey, J.B., Sankey, T.T., Kasprak, A., Bowker, M.A., and Joyal, T., 2024, Do topographic changes tell us about variability in aeolian sediment transport and dune mobility? Analysis of monthly to decadal surface changes in a partially vegetated and biocrust covered dunefield: Geomorphology, v. 447, 109021, https://doi.org/10.1016/j.geomorph.2023.109021.

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USGS Reports:

U.S. Geological Survey, 2023, Proceedings of the Fiscal Year 2022 Annual Reporting Meeting to the Glen Canyon Dam Adaptive Management Program, in Phoenix, Ariz., January 24-25, 2023: prepared by U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz.,164 p., https://www.usbr.gov/uc/progact/amp/twg/2023-01-26-twg-meeting/20230126-AnnualReportingMeeting-ProceedingsFY2022AnnualReportingMeeting-508-UCRO.pdf.

USGS Data Releases:

Sankey, J.B., East, A., Caster, J., Fairley, H., Dierker, J., Brennan, E., Pilkington, L., Bransky, N., and Kasprak, A., 2023, Aeolian and drainage classification data for various archaeological sites in Grand Canyon National Park along the Colorado River from 1973 to 2022: U.S. Geological Survey data release, https://doi.org/10.5066/P9X9ZDPK.

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National Parks Traveler, March 31, 2023, Archaeological Sites In Grand Canyon Degrading Due To Glen Canyon Dam. https://www.nationalparkstraveler.org/2023/03/grand-canyons-archaeological-sites-degrading-due-glen-canyon-dam

The New York Times, June 6, 2023, The Grand Canyon and Colorado River are in Crisis. https://www.nytimes.com/interactive/2023/06/06/climate/grand-canyon-colorado-river.html

USGS Communications and Publishing, Jun 28, 2023, Science Snippet: Archaeological sites eroding following six decades of Glen Canyon Dam operations. https://www.usgs.gov/news/science-snippet/archaeological-sites-grand-canyon-national-park-eroding-following-six-decades

National Public Radio (NPR) – KNAU Arizona Public Radio, July 14, 2023, Study: Archaeological sites in Grand Canyon eroding due to dam operations. https://www.knau.org/knau-and-arizona-news/2023-07-14/study-archaeological-sites-in-grand-canyon-eroding-due-to-dam-operations

Arizona Daily Sun, August 16, 2023, Study shows how Glen Canyon Dam has put Grand Canyon archeological sites at risk. https://azdailysun.com/news/local/govt-and-politics/study-shows-how-glen-canyon-dam-has-put-grand-canyon-archeological-site-at-risk/article_a2cfc168-3c55-11ee-b04e-7f548cb9c826.html

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

Project Lead	Charles B. Yackulic	**Principal Investigator(s)** (PI)	Bridget R. Deemer, USGS, GCMRC Charles B. Yackulic, USGS, GCMRC Lindsay Hansen, USGS, GCMRC Drew Eppehimer, USGS, GCMRC Theodore Kennedy, USGS, GCMRC
Email	cyackulic@usgs.gov		
Telephone	928-556-7379		

Goals and Objectives

Aquatic primary production is an important energy source for riverine food webs, converting sunlight, carbon dioxide, and water into simple carbohydrates via photosynthesis. In the Colorado River downriver of Glen Canyon Dam, fishes are food limited (Cross and others, 2011), and energy (carbon) produced within the river is a preferred food source relative to energy from tributaries and riparian inputs (Wellard Kelly and others, 2013). This project aims to disentangle the drivers of riverine primary production and identify their link back to fish production. We study drivers of riverine primary productivity by combining highly resolved long-term information about riverine turbidity, silt and clay concentrations, solar inputs, discharge, and gross primary productivity (gpp; via continuous oxygen and temperature measurements – data that are collected as parts of the Lake Powell project, Project A.2, and this project) with improved additional information about phosphorus (P), gas transfer, and the relative role of diatoms in affecting whole river production (Elements E.1 and E.2). These bottom-up drivers are then linked to fish populations using field-based measurements of fish growth (via mark recapture) and laboratory experiments.

Science Questions Addressed & Results

- **Hypothesis 1 (H1):** Glen Canyon Dam outflow is the biggest control on phosphorus (P) concentrations in Glen and Marble Canyons, but this influence is dampened the farther you move downstream from Glen Canyon Dam; storm-based tributary inflows also dampen the effect of Glen Canyon Dam outflow on P concentrations of the Colorado River.
- **H2:** Soluble reactive P (SRP) concentrations can be predicted based on Colorado River suspended silt-and-clay concentration and the relationship is similar to established relationships between total P and silt-and-clay.
- **H3:** There is a relatively constant relationship between suspended silt-and-clay concentration and total P concentration in the tributaries to the Colorado River through Grand Canyon.

- **H4:** A large fraction of the sediment P pool is calcite bound.
- **H5:** We expect equilibrium P concentrations in the Colorado River to be lower in the main-stem sediments and higher in the finer, backwater sediments.
- **H6:** Lower pH leads to elevated water column P bioavailability due to P release from calcium carbonates in the sediment.
- **H7:** Silt and clay concentrations negatively affect instantaneous gpp via reductions in light availability.
- **H8:** High concentrations of silt and clay in the water column have a lagged positive effect on gpp via utilization of P bound to deposited silts and clays once the water is clear again.
- **H9:** The proportion of gpp in the river due to diatom versus macrophyte production varies both seasonally and due to outflow P concentrations in Glen Canyon.
- **H10:** Macrophyte species composition and cover in Glen Canyon shifts in response to flow, temperature, and nutrients.
- **H11:** Humpback chub (*Gila cypha*) and flannelmouth sucker (*Catostomus latipinnis*) have lower basal metabolic demands than related taxa.
- **H12:** This low metabolic demand means the ecosystem can sustain large populations of these species despite relatively low primary production and that these species can survive through relatively extended periods of low food availability.

Below we focus discussion on FY 2023 efforts to address the science questions posed for each of the three elements that comprise Project E (with some recap of work done in FY 2021 and FY 2022). This includes ongoing gpp modeling work, P budgeting work, targeted P sediment incubations, vegetation mapping in Glen Canyon, and ongoing modeling work that links P, gpp, and secondary production to fish growth and population dynamics.

Project Elements

Element E.1.

Phosphorus Budgeting

In total, 423 total phosphorus (TP) samples were collected in FY 2021 and FY 2022 toward the construction of a Colorado River P budget. Initial results from samples collected in FY 2021 show that nearly 90% of the variation in TP concentrations can be explained by suspended silt and clay concentrations (n=255).

All analysis for FY 2022 samples was completed in FY 2023, but there has not been progress on the analysis of these data. Analysis of these data is planned for FY 2024.

Incubations to Examine Controls on Riverine Sediment P Release (Element E1)

In FY 2023, we published a paper describing riverine sediment P incubations that were conducted in FY 2021 (Deemer and others, 2023). The study found that Colorado and Paria River sediments can be a significant source of P to the river water column and that sediment P release is pH mediated. While the effects of pH on sediment P release were only moderate in the Glen Canyon reach, pH-driven P release from Paria River and Pearce Ferry sediments may be enough to alter nutrient limitation by shifting the stoichiometric availability of P relative to N.

In FY 2023, data from Lake Powell deltaic sediment incubations were analyzed to help understand the controls on metalimnion low dissolved oxygen events in Lake Powell. While the project was funded by the USGS Ecosystems Mission Areas (outside of the AMP), the work informs dissolved oxygen modeling requested by the GCDAMP Adaptive Management Work Group (AMWG) directive in spring/summer of 2022. River water was collected from the Colorado and San Juan River inflows to Lake Powell as well as from a small tributary (Chinle Creek) during a monsoon flooding event. Water was incubated in capped bottles in the dark for 24 hours to measure oxygen consumption rates as well as to examine nutrient dynamics. Samples were analyzed for their suspended-sediment concentration so that oxygen consumption rates could be translated into rates per unit sediment.

Preliminary results show that the Chinle Creek samples had the highest overall rates of water column oxygen consumption, the oxygen demand per unit suspended sediment (1.8-2.3 µg O_2 g^{-1} sediment h^{-1}) was up to an order of magnitude lower than in either the Colorado River water samples (3.0-25.3 3 µg O_2 g^{-1} sediment h^{-1}), or the San Juan River water samples (0.9- 15.2 µg O_2 g^{-1} sediment h^{-1}; Figure E1, panel B). Chinle Creek water samples also had distinct nutrient and carbon signatures compared with the two Lake Powell inflow sites, with 3-6 times more DOC, 6-7 times more TN, and 6-9 times more TP, one to two orders of magnitude higher dissolved nutrient concentrations, and 4 to 5 times less dissolved calcium. Molar DIN:SRP ratios declined by about 35 in the Colorado River at the North Wash boat ramp, UT, and by about 10 in the San Juan River near the Clay Hills boat ramp, UT, and remained stable in the Chinle Creek near Mexican Water, AZ (USGS gage 09379200) —with the changes observed being very small relative to the absolute ratios (Figure E1, panel F). Nutrient and calcium dynamics in the sediment incubations suggest that the metalimnion low dissolved oxygen zones that develop in Lake Powell are active with respect to nutrient cycling (Figure E1). Net dissolved phosphorus release from the incubations is consistent with previous work that noted the potential for phosphorus release from deltaic sediments in Lake Powell (Wildman and Herring, 2011). This phosphorus release may at least partially result from calcite dissolution, with calcium release measured in both the Chinle Creek and San Juan River incubations (Figure E1, panel D).

Across many of the incubations, dissolved inorganic nitrogen (DIN) was consumed, presumably due to denitrification. Still, DIN consumption was not substantial enough to push molar DIN:SRP ratios toward stoichiometric nitrogen limitation (Figure E1, panel F).

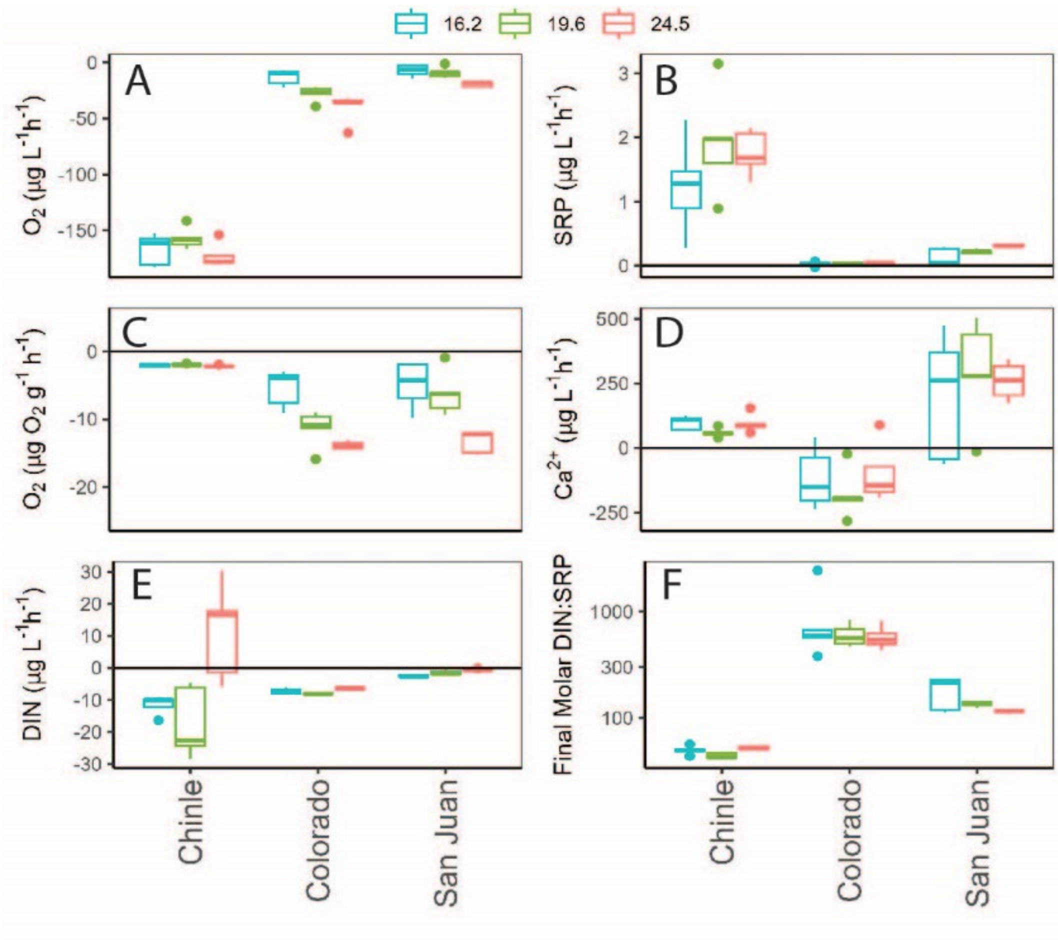

Figure E1. Rates of change for oxygen (A,C), soluble reactive phosphorus (SRP) (B), calcium (D) and dissolved inorganic nitrogen (DIN) (E), and final molar DIN:SRP ratios in the water-only incubations at three sites. Rates above zero indicate production during the incubations, whereas rates below zero indicate consumption. Colors indicate incubation temperatures in degrees Celsius. Oxygen consumption is shown as both a rate per liter of river water (A) and per gram of suspended silt and clay (C). SRP, DIN, and calcium dynamics are shown as rates per liter of river water.

Element E.2.

GPP Modeling Progress

In FY 2023, we streamlined the workflow for gpp modeling in Grand Canyon by creating a reproducible version controlled workflow in GitLab. Estimates of gpp have been generated through calendar year 2022. These estimates were presented at the 2022 annual reporting meeting held in January of 2023 and patterns suggest that temperature sensitivity of gpp differs by site (Figure E2). We plan to write a paper describing these long term gpp estimates and an associated data paper that can be versioned to include additional years' gpp estimates.

In addition, in FY 2023 we hired a new postdoctoral researcher who started in the first week of FY 2024 and is developing a faster approach for estimating gpp in Glen Canyon (building off of Payn and others, 2017).

In FY 2022, we published a paper that describes the interacting effects of sub-daily flow fluctuations and turbidity on rates of gpp. This included developing a proxy for bed grain size, g, that helps predicts weekly scale gpp, especially when combined with information about discharge and flow regime (hydropeaking or steady; Deemer and others, 2022). Our model showed higher gpp when g was low (Deemer and others, 2022), consistent with the hypothesis that silt and clay concentrations negatively affect instantaneous gpp via reductions in light availability. The study also found that steady low flows during May and June macroinvertebrate production flows (bug flows) of 2018 and 2019 boosted canyon-wide rates of gpp by about 40%.

Contribution of Diatoms vs. Macrophytes to GPP

At Lees Ferry, gpp is not correlated with P concentrations, but chlorophyll *a* is modestly correlated with P concentrations. We hypothesize that, as P increases in the water column, diatom communities increase and colonize macrophyte stems and leaves. This colonization shades the plant from sunlight, such that primary production from rooted plants will decrease. As such, the proportion of gpp in the river due to diatom versus macrophyte production likely varies both seasonally and due to outflow P concentrations in Glen Canyon. In FY 2023, we hired a postdoctoral researcher with expertise in diatom ecology to explore the long-term phytoplankton data that have been collected in the Glen Canyon tailwater as part of the Lake Powell Water Quality Monitoring Program (see Appendix 1), and they began in early FY 2024. The postdoc will also be working to develop a two-station gpp model for Glen Canyon (mentioned above), with the idea that shifts in the primary producer community may be reflected in the river's gpp signature.

Aquatic Vegetation Mapping

The purpose of the aquatic vegetation mapping project is to improve our understanding of the current macrophyte community in Glen Canyon and to provide a baseline upon which to evaluate aquatic vegetation change in response to future flow, temperature, and nutrient conditions. In addition to existing underwater imagery taken in 2016 (n=2,738 photos) and 2019 (n=26,001 photos), an additional 19,345 underwater images were collected prior to, during, and after the spring disturbance flow in 2021. These images document the composition and cover of aquatic macrophytes, macroalgae, and bryophytes in Glen Canyon at two established transects in the upper (~-13 RM) and lower (~-4 RM) sections of the Colorado River, which overlap with sites currently sampled for rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) as part of the TRGD Project (1A, 1C; Project Element H.2).

In 2022, additional images were taken in TRGD sites 1A and 1C to expand the use of this application to all 250-m segments in the TRGD reaches, for the purpose of relating macrophyte cover and *Potamogeton* density to brown trout population size.

Image labeling (image-based classification training data collection) was conducted in 2022 using MakeSense.ai software. This element of project E did not progress in FY 2023 due to a lack of staff to lead this work and conflicting demands on staff time.

Storm Phosphorus Incubations

We collected Paria River storm samples and incubated storm water with Colorado River water to quantify how storm-based tributary inputs of silt and clay may support lagged positive effects on gpp via newly available P. Results are included in the Deemer and others, 2023 paper described in Project Element E1. In brief, factor of four increases in water column TDP were maintained throughout the 7-day storm simulation experiment (from <1.5 µg L-1 TDP pre-storm to 6.7 µg L-1 TDP post storm), showing that tributary storm inputs can elevate riverine P availability.

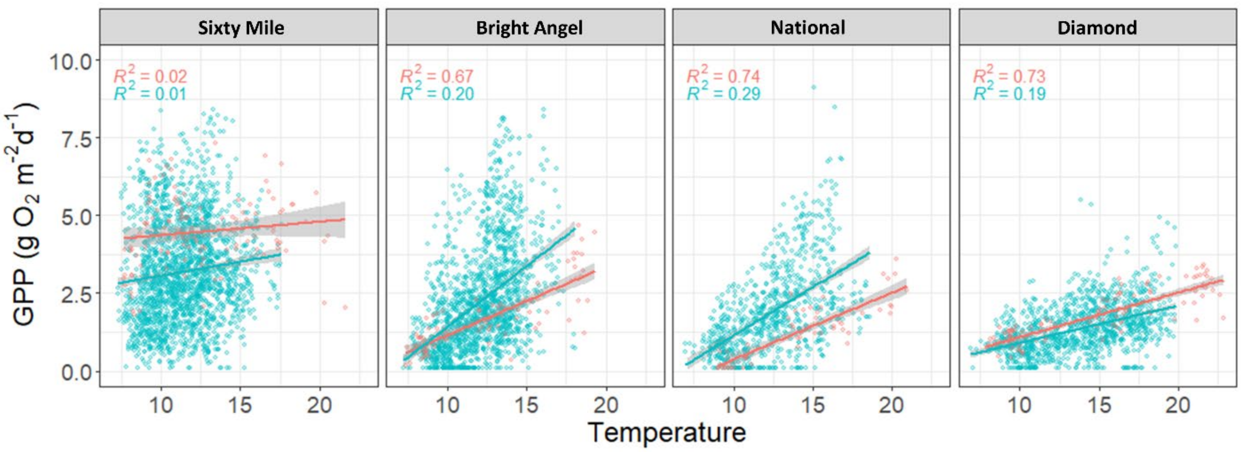

Figure E2. The relationship between gpp and temperature for 2012-2021 (blue dots) and for 2022 (red dots) at four sites representing reaches ending at the USGS gaging stations: Colorado River above Little Colorado River near Desert View, AZ, "Sixty Mile" 09383100, Colorado River near Grand Canyon, AZ, "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. These data represent only those gpp estimates calculated in low turbidity conditions (turbidity <12 FNU). By removing gpp values where turbidity is high (>12 FNU), we can see a more significant relationship between habitat variables and gpp. Gpp estimates from 2022 are colored in red to represent warm-water releases from Glen Canyon Dam.

Element E.3.

Laboratory Determinations of Fish Metabolic Rates

One objective of Project Element E.3 is to measure standard and active metabolic rates of large-bodied native fishes in the Grand Canyon (e.g., humpback chub and flannelmouth sucker) under laboratory conditions. These fishes dominate the biomass of Grand Canyon fish communities, but past studies have relied on metabolic rates of related species that may not be reliable surrogates. In FY 2023, the equipment necessary to measure fish metabolism in a laboratory setting was purchased and we plan to begin initial trials in the winter of FY 2024.

Ecosystem Models

Another objective of Project Element E.3 is to integrate data in ecosystem models to better understand how nutrients, flow, and discharge directly and indirectly affect other trophic levels. This year, progress was made in modeling flannelmouth sucker, humpback chub, and rainbow trout growth as a function of bottom-up environmental drivers.

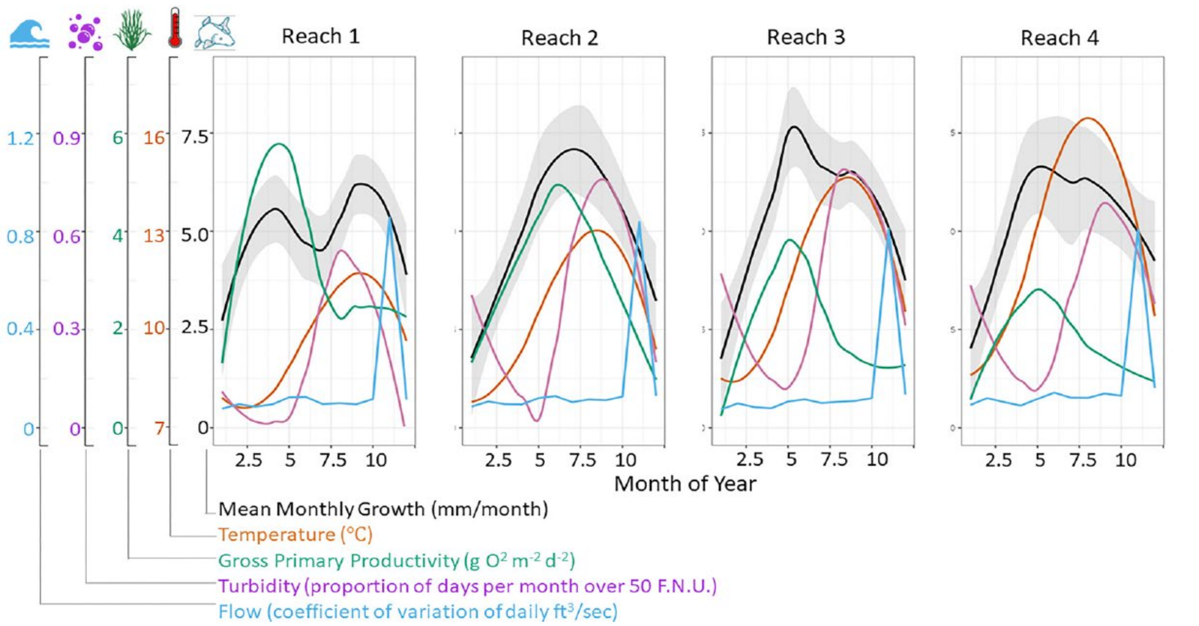

Figure E3. Smoothed predicted mean monthly growth in length (mm/month; black line) for a 200 mm flannelmouth sucker for four reaches across month intervals with 95% credible intervals (shown in gray). Overlaid are the mean values of environmental covariates: temperature (red line), GPP (green line), and turbidity (purple line), with High-Flow Experiments indicated (vertical blue line). Plots correspond with: Reach 1) Paria River to Little Colorado River, Reach 2) Little Colorado River to Bright Angel Creek, Reach 3) Bright Angel Creek to National Creek, and Reach 4) National Creek to Diamond Creek. Taken from Hansen and others, 2023.

A manuscript was published in which flannelmouth sucker growth is modeled as a function of gpp and water temperature (Hansen and others, 2023). The paper finds that variation in gpp is a significant driver of flannelmouth sucker growth (Figure E3). For example, the growth model suggests that the 38% increase in canyon-wide gpp during May and June bug flows (Deemer and others, 2022) would correspond to an increase in flannelmouth sucker growth of 1.6 mm per month, or approximately the same effect as warming the river by 1.1 degrees Celsius (Hansen and others, 2023).

This work represents a first step in developing ecosystem models to address questions about metabolic demand. In FY 2023, we fit similar models to humpback chub growth and have begun drafting a manuscript describing these results. We tested various flow metrics, along with temperature, gpp, and turbidity as predictors of humpback chub growth in both juvenile chub monitoring (JCM) and JCM-west reaches.

A second manuscript was published describing an approach to estimate prey production rates in Lees Ferry by integrating rainbow trout growth and abundances, literature values for rainbow trout bioenergetics, and drift estimates taken through Project F (Yard and others, 2023). This modeling approach could be extended to downstream fish to form the backbone of future ecosystem modeling. The paper links declines in prey production to changing reservoir conditions. Another manuscript (described in Project F) models one decade of rainbow trout growth in Glen Canyon. The paper quantifies the effects of water quality (both P and water temperature) and compares these to effects of competition, experimental flows, and solar insolation (Korman and others, 2022). Both papers note that declining SRP concentrations in Glen Canyon Dam outflows have negative effects on food web production. They also suggest that higher outflow SRP concentrations are more likely when Lake Powell is full (Korman and others, 2022; Yard and others, 2023).

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Project E Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$200,049	$10,500	$13,881	$0	$0	$28,330	**$252,760**
Actual Spent	$124,802	$3,102	$32,656	$0	$0	$20,268	**$180,829**
(Over)/Under Budget	**$75,247**	**$7,398**	**($18,775)**	**$0**	**$0**	**$8,062**	**$71,931**

COMMENTS

FY23 Comments:
- Underspent Salaries is due to HR-delays in hiring and staff turnover.
- Underspent Travel & Training is due to being understaffed and fieldwork and conference travel planned for FY23 was delayed.
- Overspent in Operating Expenses is for purchases of necessary lab equipment.

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

Presentations:

Brown, P., Moody, E., Muehlbauer, J., Deemer, B., Yackulic, C., Corman, J., and Kennedy, T., 2023, The role of calcium carbonate in gross primary production in the Little Colorado River, AZ, and implications for humpback chub growth rates—presentation: Desert Fishes Council Annual Symposium, Bishop, Ca.

Deemer, B.R., 2022, Beyond eco-flows—Understanding biogeochemical links between limnology and management in human-made reservoirs—presentation: Joint Aquatic Science Meeting, Grand Rapids, Mich.

Deemer, B.R., 2023, Dams and drought—How Lake Powell and the southwest mega-drought have fundamentally altered downstream nutrient dynamics: Seminar at University of Nebraska, Lincoln.

Deemer, B.R., 2023, Dams and drought—How Lake Powell has altered downstream nutrient dynamics: Science Seminar at Washington State University, Vancouver.

Deemer, B.R., Reibold, R., Fatta, A., Corman, J., Yackulic, C.B., and Reed, S., 2022, Links between drought and river nutrition—Phosphorus export from Glen Canyon Dam under declining reservoir elevations—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, Flagstaff, Ariz.

Deemer, B.R. and Yackulic, C.B., 2022, Turning the red river green—An environmental flow increases primary productivity in the Colorado River—presentation: U.S. Geological Survey Friday Findings Seminar Series, https://www.usgs.gov/mission-areas/ecosystems/news/fridays-findings-january-14th-2022.

Dibble, K.L., 2023, Aquatic plants, food webs, and fish populations in the Colorado River in Glen Canyon Dam National Recreation Area: Outreach river trip and science presentation to the 2022 Native Youth Science Camp.

Dibble, K.L., Bruckerhoff, L.A., Yackulic, C.B., Schmidt, J.C., Bestgen, K.R., Kennedy, T.A., Mihalevich, B.A., Neilson, B.T., Wang, J., and Wheeler, K., 2022, Forecasting the influence of climate change, water storage decisions, and consumptive use on fishes of the Colorado River basin—virtual oral presentation and panel: DOI Turbine Talk Webinar Series focused on 'USGS Science on Climate Impacts on Hydropower.'

Dibble, K.L., Yard, M., Tusso, R., Buscombe, D., 2022, Aquatic vegetation in Glen Canyon—Observations following a spring disturbance flow—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, Phoenix, Ariz.

Hansen, L.E., and Yackulic, C.B., 2022, Linking ecosystem processes to consumer growth rates—Gross primary productivity and temperature drive fish growth—presentation: Joint Aquatic Science Meeting, Grand Rapids, Mich.

Journal Articles:

Deemer, B.R., Yackulic, C.B., Hall, R.O., Jr., Dodrill, M.J., Kennedy, T.A., Muehlbauer, J.D., Topping, D.J., Voichick, N., and Yard, M.D., 2022, Experimental reductions in sub-daily flow fluctuations increased gross primary productivity for 425 river kilometers downstream: PNAS Nexus, v. 1, no. 3, pgac094, https://doi.org/10.1093/pnasnexus/pgac094.

Deemer, B.R., Reibold, R.H., Fatta, A., Corman, J.R., Yackulic, C.B., and Reed, S.C., 2023, Storms and pH of dam releases affect downstream phosphorus cycling in an arid regulated river: Biogeochemistry, v. 165, p. 57–74, https://doi.org/10.1007/s10533-023-01064-5.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., 2023, Linking ecosystem processes to consumer growth rates—Gross primary productivity as a driver of freshwater fish somatic growth in a resource-limited river: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 9, p. 1456-1469, https://doi.org/10.1139/cjfas-2022-0229.

Korman, J., Deemer, B., Yackulic, C.B., Kennedy, T.A., and Giardina, M., 2022, Drought related changes in water quality surpass effects of experimental flows on trout growth downstream of Lake Powell reservoir: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 3, p.

424-438, https://doi.org/10.1139/cjfas-2022-0142.
Yard, M.D., Yackulic, C.B., Korman, J., Dodrill, M.J., and Deemer, B.R., 2023, Declines in prey production during the collapse of a tailwater rainbow trout population are associated with changing reservoir conditions: Transactions of the American Fisheries Society, v. 152, no. 1, p. 35-50, https://doi.org/10.1002/tafs.10381.

USGS Data Releases:

Deemer, B.R., Yard, M.D., Voichick, N., Goodenough, D.C., Bennett, G.E., Hall Jr., R.O., Dodrill, M.J., Topping, D.J., Gushue, T., Muehlbauer, J.D, Kennedy, T.A., and Yackulic, C.B., 2022, Gross primary production estimates and associated light, sediment, and water quality data from the Colorado River below Glen Canyon Dam: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZS6YLV.

Hansen, L.E., and Yackulic, C.B., 2022, Mark-recapture and environmental data used to predict flannelmouth sucker *(Catostomous latippinis*) growth rates within the Colorado River in the Grand Canyon from April 2012 to October 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9852I1G.

Korman, J., Yard, M., and Deemer, B.R., 2023, Rainbow trout growth data and growth covariate data from Glen Canyon, Colorado River, Arizona, 2012-2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9XU3SQP.

Reibold, R.H., Fatta, A., Voichick, N., Goodenough, D., and Deemer, B.R., 2023, Phosphorus, nitrogen, carbon, calcium, pH, and dissolved oxygen data from incubations of Colorado River water and sediment and associated ambient river water measurements: U.S. Geological Survey data release, https://doi.org/10.5066/P9L4JG9D.

Yackulic, C.B., Yard, M.D., Korman, J., Dodrill, M.J., and Deemer, B.R., 2022, Proximal and distal factors associated with the decline in secondary invertebrate prey production in the Colorado River, Glen Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9UZTYPV.

Project F: Aquatic Invertebrate Ecology

Project Lead	Theodore Kennedy	**Principal Investigator(s)** (PI)	Theodore Kennedy, USGS, GCMRC Anya Metcalfe, USGS, GCMRC Jeff Muehlbauer, USGS, Alaska Coop Unit Morgan Ford, USGS, GCMRC Charles Yackulic, USGS, GCMRC Mike Dodrill, USGS, WFRC
Email	tkennedy@usgs.gov		
Telephone	(928) 556-7374		

Goals and Objectives

A principal goal of our work this year was the continued monitoring of invertebrate population abundance and diversity using a variety of sampling methods. To monitor the invertebrate food base in Grand Canyon, we continued partnering with river guides and education groups through our community science light trapping project. This project has been ongoing since 2012 and provides a powerful tool for tracking invertebrate population response to adaptive management experimentation and changing environmental conditions. Starting in 2017, a subset of the community science participants has also been equipped with bat acoustic activity monitors, and this bat monitoring effort was continued in 2023. In collaboration with Oregon State University (OSU), we also continued monitoring invertebrate diversity in the main-stem Colorado River and tributaries using environmental DNA (eDNA) techniques. We also continued monthly food base monitoring in the Glen Canyon reach to inform trends in trout populations, and we continued food base data collections in reaches where humpback chub (*Gila cypha*) populations appear to be growing (see Project G).

In 2023, intensive food base monitoring before, during, and after the April 2023 High-Flow Experiment (HFE) were also conducted in Glen Canyon to understand how this flow disturbance affects food availability. To make predictions about how changing environmental conditions and dam operations may affect invertebrate populations, collaborators at OSU have continued to develop population models and run different scenarios. In 2023, we also continued diet studies on native and nonnative fishes using non-lethal methods that include DNA analysis of fish feces and stable isotope analysis of fish fin clips. Starting in 2023, collaborators at OSU are also analyzing parasites from fish fecal samples using in-kind funding they obtain from OSU. We are using these non-lethal methods for quantifying fish feeding habits and parasites to honor Tribal concerns about the taking of life. Our group also opportunistically performed diet analysis on nonnative smallmouth bass that were euthanized as part of ongoing removal efforts in Glen and Grand Canyons to understand feeding habits of these fish.

Research and monitoring of invertebrate assemblages described in Project F informs the LTEMP Goal for Natural Processes. Project F also provides essential context and data that are used by other projects in evaluation of other LTEMP goals.

For example, invertebrate monitoring data are used by Project E (Controls on ecosystem productivity) to identify the extent to which changing nutrient levels are propagating up through the food web. Invertebrate monitoring data collected in Project F also aid interpretation of seasonal and annual abundance trends in humpback chub (Project G) and nonnative rainbow trout (Project H), because aquatic invertebrates represent the food base for these fish. Project F also integrates and uses data from other projects, particularly Project A (streamflow, water quality, and sediment transport) and Project B (habitat mapping), to identify how changing environmental and habitat conditions affect invertebrate populations. Details of this ongoing project are provided in the GCMRC FY 2021–23 Triennial Work Plan (U.S. Department of the Interior, 2020).

Project Elements

Element F.1. Invertebrate Monitoring in Grand Canyon

Community science light trapping has been the backbone of our invertebrate monitoring in Grand Canyon since 2012 (Kennedy and others, 2016; see Figure F1). In 2023, community science sampling yielded 614 light trap samples of adult aquatic insects, over more than 285 miles of the Colorado River, from April-October. Preliminary analysis of the 2023 light trap samples will be presented at the Annual Reporting Meeting in January 2024.

We launched one Grand Canyon river trip in April 2023 to quantify invertebrate drift concentrations approximately every ten miles throughout Glen, Marble, and Grand Canyons. These drift data will be compared to similar drift data that were collected annually in 2017-2022 to quantify variation in invertebrate assemblages and drift biomass. As part of this annual river trip, drift is collected at juvenile humpback chub monitoring locations (Little Colorado River confluence and Fall Canyon). Collaborators from Oregon State University also participated on this April 2023 trip to collect eDNA samples from tributary and main-stem locations to evaluate suitability of this new method for quantifying diversity and species richness of invertebrate assemblages (see F.3, Invertebrate monitoring in Tributaries, below).

In 2023, community scientists also collected acoustic bat activity data paired with 361 of the light trap samples. Paired bat acoustic and insect monitoring data from 2017-2020 were recently published, revealing that bat activity (# of calls per hour) was positively related to the abundance of aquatic flies (Diptera) in Grand Canyon (Metcalfe and others, 2023).

Furthermore, the abundance of aquatic flies as a predictor of bat activity outcompeted all other invertebrate prey categories (e.g., moths, terrestrial insects) and environmental variables (e.g., vegetation cover, lunar phase, air temperature) in models.

To improve opportunities for diverse audiences to learn about the scientific process and participate in monitoring, GCMRC has partnered with Grand Canyon Youth to launch Partners in Science river trips for more than 20 years. A video highlighting this collaboration can be found here: https://www.freshwatersillustrated.org/what-you-take-away.

Each of these Partners in Science trips engage approximately 20 high school age students in data collection and monitoring activities including light trapping and bat acoustic monitoring reported here. One of the three Partners trips launched in 2023 was comprised entirely of Tribal youth participants.

Element F.2. Invertebrate Monitoring in Glen Canyon

In FY 2023 our group continued long-term monitoring of the aquatic food base in the Lees Ferry sport fishery. This monitoring includes monthly drift, sticky trap, and light trap sampling from Glen Canyon Dam (RM -15) to the Lees Ferry boat ramp (RM 0). We also conducted intensive drift sampling before, during, and after the April 2023 HFE to document effects of this flow disturbance on prey availability in Glen Canyon. Collectively, these data collection efforts will allow us to track invertebrate populations in the Lees Ferry sport fishery using a variety of sampling methods on robust spatial and temporal scales.

Element F.3. Invertebrate Monitoring in Tributaries

In response to a request from the National Park Service, our group continued studies of the food base in Bright Angel Creek associated with ongoing trout removal efforts and the reintroduction of humpback chub in 2019. In coordination with the USGS-Youth and Education in Science (YES) office we hired a summer intern to help move forward on processing backlogged samples collected in prior years. This intern processed ten backlogged benthic samples from Bright Angel Creek in FY 2023. This work will allow us to explore how the food web in Bright Angel Creek has responded to these management actions. Analysis of these data is ongoing, and a manuscript describing these studies is under development.

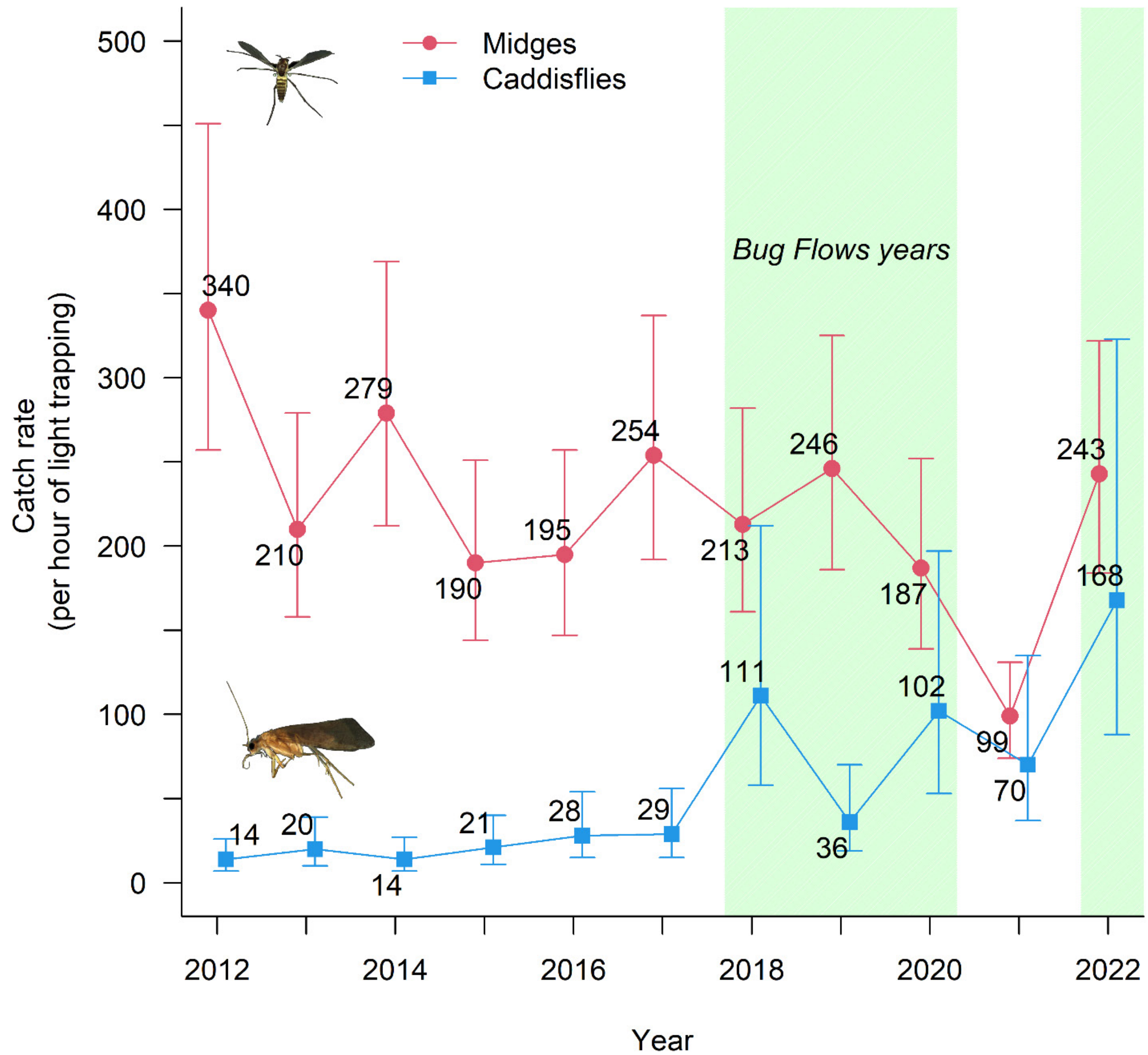

Figure F1. Average caddisfly (blue line) and midge abundance (red line) collected in community science light traps from 2012 through 2022. Annual average values appear above each point and are estimated from a mixed-effects model that accounts for variation in sampling effort across reaches and across years. Error bars represent one standard error. Bug Flows were tested in 2022 but not in 2021. Notably, the abundance of caddisflies increased by 140% in 2022 compared to the year prior while the abundance of midges increased by 145% in 2022 compared to the year prior; both of these increases are statistically significant ($p < 0.01$). Provisional data, subject to change.

Unregulated tributaries within the Grand Canyon have the potential to act as sources of invertebrate biodiversity for the main stem, although the degree to which this occurs is unknown. To address this question of invertebrate diversity in main stem versus tributary locations, we have been collaborating with Oregon State University scientists and graduate students to use an eDNA metabarcoding approach to assemble a data set of invertebrate community diversity in tributaries and the main stem.

In 2023, collaborators at Oregon State collected eDNA water samples from 70 locations in the Grand Canyon including: 17 samples from the main-stem Colorado River, 21 tributary sites near their confluence with the main stem, 15 tributary sites at 2km upstream from their confluence with the main stem, 11 sites at 4 km upstream from their confluence with the main stem, and 6 spring locations that do not connect to the main stem. Samples from the 2022 campaign have been processed and will be presented at the Annual Reporting Meeting in January 2024. Sampling in prior years revealed considerable invertebrate diversity across tributary sites while invertebrate diversity in the main stem was lower and varied comparatively little across sites compared to tributaries. The purpose of the 2023 sampling design, which included sampling at multiple locations within each tributary (i.e., at confluence, 2km and/or 4km upstream from confluence), was to determine the extent to which invertebrate communities in individual tributaries vary in their composition and diversity.

Element F.4. Fish Diet Studies

This element includes analysis of existing rainbow and brown trout diet data from Lees Ferry. It also includes collection of diet samples for native and other nonnative fishes in Grand Canyon. In FY 2023, we launched one river trip and collaborated with partners on two other river trips to collect samples of fish feces for DNA analysis and fin clips for stable isotope analysis on a seasonal basis (i.e., April, July, October). The total number of fin clip and fecal samples collected in 2023 was: flannelmouth sucker - 293, humpback chub - 119, rainbow trout - 35. Fecal samples will be analyzed using the same DNA laboratory process that has been successful at identifying invertebrate communities from water samples (see Element F.3, above). DNA analysis of fecal samples is being used to determine feeding habits and evaluate parasites of fishes (funding for parasite analysis is being provided by Oregon State University and USGS). Fecal samples from April 2022 and April 2023 have been processed and will be presented at the Annual Reporting Meeting in January 2024. Our lab also analyzed the diet contents from over 50 smallmouth bass that were euthanized as part of mechanical removal efforts to understand their feeding habits.

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Kennedy, T.A., Muehlbauer, J.D., Yackulic, C.B., Lytle, D.A., Miller, S.W., Dibble, K.L., Kortenhoeven, E.W., Metcalfe, A.N., and Baxter, C.V., 2016, Flow management for hydropower extirpates aquatic insects, undermining river food webs: BioScience, v. 66, no. 7, p. 561-575, https://doi.org/10.1093/biosci/biw059.

Metcalfe, A.N., Fritzinger, C.A., Weller, T.J., Dodrill, M.J., Muehlbauer, J.D., Yackulic, C.B., Holton, P.B., Szydlo, C.M., Durning, L.E., Sankey, J.B., and Kennedy, T.A., 2023, Insectivorous bat foraging tracks the availability of aquatic flies (Diptera): The Journal of Wildlife Management, v. 87, no. 5, e22414, https://doi.org/10.1002/jwmg.22414.

U.S. Department of the Interior, 2020, Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2021-2023—Final approved by the Secretary of the Interior—December 2, 2020: Flagstaff, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, and Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 384 p., http://gcdamp.com/images_gcdamp_com/5/5d/GCMRC_TWP2021-23_December2_2020_ApprovedBySecretary.pdf.

Project F Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$467,043	$17,039	$37,583	$0	$0	$65,850	**$587,515**
Actual Spent	$476,820	$12,720	$33,401	$0	$0	$66,011	**$588,952**
(Over)/Under Budget	**($9,777)**	**$4,319**	**$4,182**	**$0**	**$0**	**($161)**	**($1,437)**

COMMENTS

FY23 Comments:
- Overspent Salaries is due to promotions among staff and overtime associated with staff participation on the summer seining trip in support of fish diet studies.
- Underspent Travel & Training is due to emphasis on camping for Glen Canyon trips instead of lodging and only limited conference attenance.
- Underspent in Operating Expenses to offset seining trip and salary.

Project F Deliverables: Aquatic Invertebrate Ecology

Presentations:

Kennedy, T.A., 2023, Experimental bug flows increase algae production and insect diversity in the Colorado River, Grand Canyon: Annual River Guides Training Seminar, Marble Canyon, Ariz., April 2023.

Kennedy, T.A., 2023, Little bugs, big data, and Colorado River adaptive management—virtual presentation to Utah State University 'Colorado River' class, March 2023.

Kennedy, T.A., Muehlbauer, J., Metcalfe, A., Deemer, B., Ford, M., Szydlo, C., Behn, K., and Yackulic, C., 2023, Experimental bug flows enhance natural processes that sustain the Colorado River ecosystem—presentation: Glen Canyon Dam Adaptive Management Program, Technical Work Group meeting, Flagstaff, Ariz., June 2023.

Kennedy, T.A., Muehlbauer, J., Szydlo, C., and Metcalfe, A., 2023, Project F—Bug flows and food base update—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Kennedy, T.A., Mihalevich, B., Deemer, B., and Palmquist, E., 2023, Science update—Lake Powell, riparian vegetation, and bug flows—presentation: Glen Canyon Dam Adaptive Management Program, Adaptive Management Work Group meeting, Phoenix, Ariz., February 2023.

Lytle, D.A., Kurthen, A., and Freedman, J., 2023, Molecular and modeling tools for tracking food base dynamics in changing environments—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Metcalfe, A. and Fritzinger, C., 2023, River bats! Measuring bat activity along the Colorado River: Annual River Guides Training Seminar, Marble Canyon, Ariz., April 2023.

Metcalfe, A., and Kennedy, T., 2022, Community scientists shed light on aquatic foodwebs in Grand Canyon, Arizona, USA—Invited oral presentation for session on 'Uncertainty and error in hydrological citizen science observations': American Geophysical Union, Chicago, Ill.

Metcalfe, A., Kennedy, T., Muehlbauer, J., Starbuck, M., and Lytle, D., 2023. Evaluating bug flows—Phenology, diet, and growing conditions of a Hydropsychid caddisfly during a stable flow experiment—presentation: Society for Freshwater Science, Brisbane, Australia, May 2023.

Starbuck, M., Metcalfe, A., Muehlbauer, J., Lytle, D., and Kennedy, T., 2023, A deep dive on net-spinning caddisflies (*Hydropsyche oslari*)—poster presentation at Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Journal Articles:

Metcalfe, A.N., Fritzinger, C.A., Weller, T.J., Dodrill, M.J., Muehlbauer, J.D., Yackulic, C.B., Holton, P.B., Szydlo, C.M., Durning, L.E., Sankey, J.B., and Kennedy, T.A., 2023, Insectivorous bat foraging tracks the availability of aquatic flies (Diptera): The Journal of Wildlife Management, v. 87, no. 5, e22414, https://doi.org/10.1002/jwmg.22414.

Metcalfe, A.N., Muehlbauer, J.D., Ford, M.A., and Kennedy, T.A., 2023, Colorado River basin—chapter 11, in Delong, M., Jardine, T., Benke, A., and Cushing, C., eds., Rivers of North America: Cambridge, Mass., Academic Press, p. 463-509, https://www.elsevier.com/books/rivers-of-north-america/delong/978-0-12-818847-7.

Roe, C.C., Holiday, O., Upshaw-Bia, K., Benally, G., Williamson, C.H.D., Urbanz, J., Verocai, G.G., Ridenour, C.L., Nottingham, R., Ford, M.A., Lake, D.P., Kennedy, T.A., Hepp, C.M., and Sahl, J.W., 2023, Biting midges (Diptera: Ceratopogonidae) as putative vectors of zoonotic *Onchocerca lupi* (Nematoda: Onchocercidae) in northern Arizona and New Mexico, southwestern United States: Frontiers in Veterinary Science, v. 10, 1167070, https://doi.org/10.3389/fvets.2023.1167070.

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

Project Lead	Maria Dzul	**Principal Investigator(s)** (PI)	Maria Dzul, USGS, GCMRC Charles B. Yackulic, USGS, GCMRC Lindsay Hansen, USGS, GCMRC Pilar Rinker, USFWS Michael Pillow, USFWS David Ward, USFWS
Email	mdzul@usgs.gov		
Telephone	313-407-0790		

Goals and Objectives

- Accurately estimate the abundance of various life stages (e.g., juveniles, subadults, adults) of humpback chub (HBC) to inform triggers associated with the 2016 Biological Opinion (U.S. Department of the Interior, 2016).
- Use models to learn about relationships between environmental factors and HBC life history to forecast impacts of management actions on future abundances.
- Improve estimation approaches to obtain more precise abundance estimates, including assessing the potential benefits of new technologies and(or) sampling methods.
- Quantify the efficacy of existing management actions, and potential alternative management strategies, for increasing or maintaining HBC abundances.

Project Elements

Element G.1. Humpback Chub Population Modeling

Science Questions/Hypotheses Addressed

- What are the trends in abundances for various life history stages of HBC (i.e., juveniles, subadults, and adults) in the Little Colorado River and in western Grand Canyon and what do these indicate for future adult population abundances (i.e., increasing, decreasing, stable)?
- How do survival and growth compare among different groups of HBC within Grand Canyon (i.e., HBC that spawn in the Little Colorado River, but rear in either the nearby Colorado River or the Little Colorado River or those that rear and spawn in the western Grand Canyon)?
- How do environmental factors influence population dynamics of HBC?

Results

Humpback chub abundance estimates were reported to stakeholders as part of the annual reporting meeting of the GCDAMP in January 2022. For Little Colorado River spawners, juvenile and subadult abundances have been low in recent (~3-4) years and subadult abundances in the Little Colorado River and in the juvenile chub monitoring (JCM)-east reach were below the thresholds associated with the Tier-1 trigger (U.S. Department of the Interior, 2016).

Adult abundances remain high and above the trigger value of 9000 and have remained stable over the last 3 years. Warming water temperatures have led to faster growth of subadults in JCM-east, and this may affect population turnover rates in the future. For western Grand Canyon, adult abundances have increased over the last 5 years, though uncertainty is high. Abundance estimates from 2023 are not yet available but will be reported at the FY 2023 annual reporting meeting in January 2024.

In FY 2023, modeling innovations have focused on 1) utilizing array detections in the Little Colorado River to improve abundance estimation and learn more about migration dynamics of Little Colorado River spawning adult HBC and other native species (see item G.4) and 2) methods for differentiating emigration from mortality in western Grand Canyon to obtain an estimate of true survival. In terms of the latter, we have used simulation to evaluate the Barker resight model (Barker, 1997) as a tool to use auxiliary sightings of HBC outside JCM-west to estimate true survival within JCM-west. However, simulations concluded there may be substantial survival biases associated with using fixed sites for resight with the Barker model, suggesting a different approach is necessary. Additionally, we have started a sonic tag study in JCM-west reach to provide additional information about emigration and movement probabilities, which should improve abundance and survival estimation.

Element G.2. Annual Spring/Fall Humpback Chub Abundance Estimates in the Lower 13.6 km of the Little Colorado River

Science Questions/Hypotheses Addressed

- Are adult and subadult HBC abundance estimates above the abundance thresholds identified as triggers for trout removal as part of the 2016 Biological Opinion (U.S. Department of the Interior, 2016)?
- What are the trends in abundances for various life history stages of HBC (i.e., juveniles, subadults, and adults) in the Little Colorado River?

Results

In 2023, USFWS and volunteers conducted four sampling trips (during April, May, September, and October) to monitor humpback chub in the Little Colorado River. During spring 2023, we estimated that there were 15,900 (Standard Error [SE] = 400) HBC ≥150 mm total length (TL), of which 13,900 (SE = 230) were ≥200 mm TL in the Little Colorado River (Figure G1).

These numbers represent an increase from the spring 2022 estimates and the highest point estimates recorded since the USFWS Little Colorado River monitoring program began in 2000 (2020 spring estimates were not obtained because of COVID impacts). In fall 2023, it was estimated that there were 4,000 (SE = 400) HBC ≥150 mm TL in the Little Colorado River. Of these fish, an estimated 2,000 (SE = 240) were ≥200 mm TL (Figure G1). These fall estimates are similar to fall adult abundance numbers from recent years.

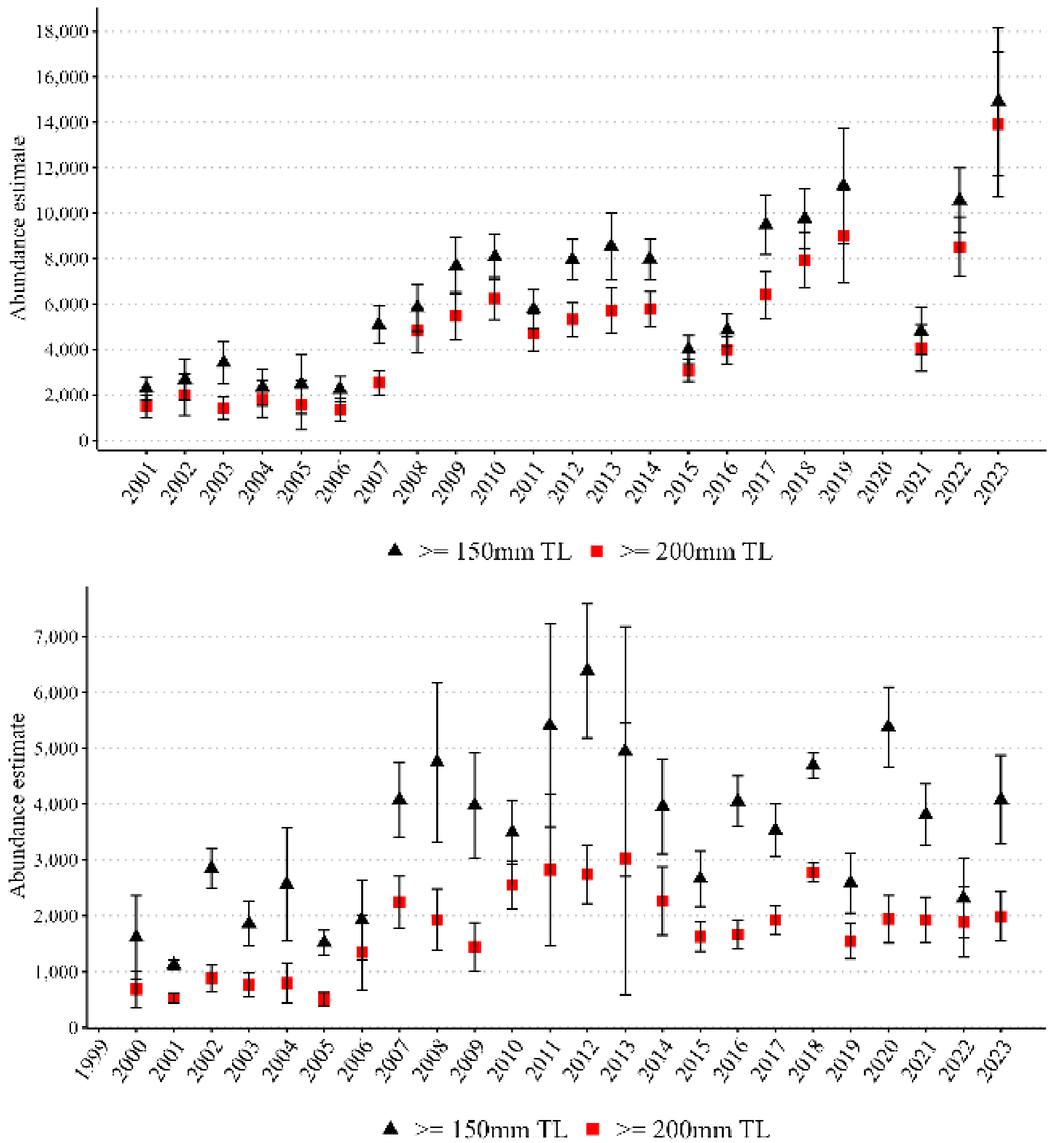

Figure G1. Chapman Petersen abundance estimates (±95% CI) of humpback chub ≥150 mm total length (TL) and ≥200 mm TL in the Little Colorado River (0-13.57 river km) during spring 2001-2023 (upper panel) and fall 2000-2023 (lower panel). Note: No spring 2020 estimates obtained because of COVID impacts. Provisional data, subject to change.

Element G.3. Juvenile Humpback Chub Monitoring near the Little Colorado River Confluence

Science Questions/Hypotheses Addressed

- Are adult and subadult HBC abundance estimates above the abundance thresholds identified as triggers for trout removal as part of the 2016 Biological Opinion (U.S. Department of the Interior, 2016).
- What are the trends in abundances for various life history stages of HBC that spawn in the Little Colorado River and what does this indicate for future adult population abundances?
- What environmental factors influence juvenile abundances?

Results

This Project Element, along with Elements G.2 and G.4, are used to model HBC abundances that are reported to stakeholders (see G.1). In 2023, three sampling trips (in April, July, and October) occurred to the juvenile chub monitoring (JCM)-east reach and one trip (June) to the Little Colorado River.

Across all three main-stem trips to JCM-east, catch of flannelmouth sucker *Catostomus latipinnis* was highest (5731), followed by humpback chub (3896), fathead minnow *Pimephales promelas* (1577), bluehead sucker *Catostomus discobolus* (863), rainbow trout *Oncorhynchus mykiss* (363), channel catfish *Ictalurus punctatus* (186), carp *Cyprinus carpio* (88), speckled dace *Rhinichthys osculus* (72), green sunfish *Lepomis cyanellus* (43), black bullhead *Ameiurus melas* (15), striped bass *Morone saxatilis* (9), gizzard shad *Dorosoma cepedianum* (8), brown trout *Salmo trutta* (7), plains killifish *Fundulus zebrinus* (7), black crappie *Pomoxis nigromaculatus* (6), bluegill *Lepomis macrochirus* (4), red shiner *Cyprinella lutrensis* (2), yellow bullhead *Ameiurus natalis* (2), and walleye *Sander vitreus* (1). Catch of HBC >99 mm TL was 323 in April, 495 in July, and 553 in October. In addition, the number of HBC between 40-99 mm TL was 612 in April, 585 in July, and 1319 in October.

Age-0 abundance estimates from the Little Colorado River from the June sampling trip indicates abundance was relatively high in 2023 compared to 2013-2022; however, the size distribution of age-0 fish was lower than in past years, with most age-0 HBC <40 mm total length (Figure G2). The small size of age-0 HBC is likely due to the large, prolonged floods in the Little Colorado River that occurred in winter and spring of 2023 and perhaps higher densities than are typical. In addition to sampling, the July Little Colorado River trip also collected ~600 small juvenile HBC (<40 mm TL) for the Southwestern Native Aquatic Resources and Recovery Center (SNARRC).

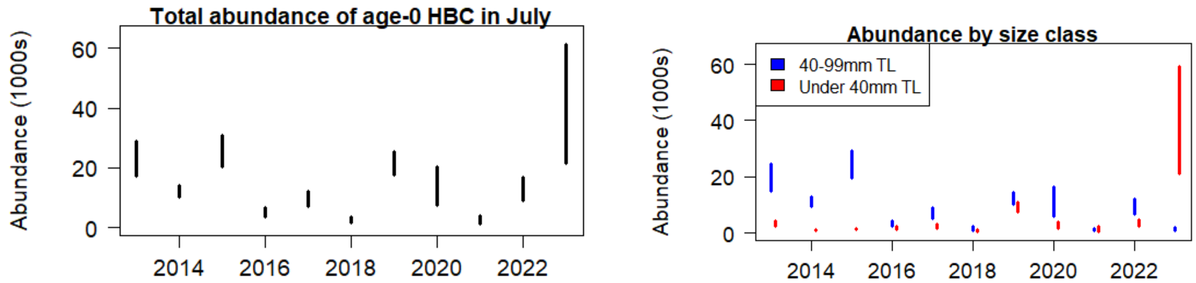

Figure G2. Abundances of total age-0 humpback chub from the June/July Little Colorado River sampling trip. The left panel indicates total abundance in each year, whereas the right panel shows abundances by size class, where size class is either 40-99 mm total length (TL) or under 40 mm TL. Provisional data, subject to change.

Element G.4. Remote PIT-Tag Array Monitoring in the Little Colorado River

Science Questions/Hypotheses Addressed

- How does the number of migrating HBC differ across years? Is the number (or proportion) of spawning HBC influenced by hydrologic factors?
- How does the hydrologic cycle influence timing of native fish migration?

Results

An array system in the Little Colorado River about 1.8 river kilometers (rkm) upstream of the confluence detects passive integrated transponder (PIT) tags of marked fishes. By a convention established decades ago, distance in the Little Colorado River is described in kilometers from the confluence with the Colorado River. Distance in the Colorado River is described in river miles. In combination with USFWS monitoring data from the lower Little Colorado River (G.2), the detection data from this array system was used to estimate abundance of migratory and resident fishes in the Little Colorado River during spring of 2021 and 2022 (Figure G3). Abundance estimates were relatively similar in 2021 and 2022 for humpback chub, flannelmouth sucker, and bluehead sucker. In addition, most individuals in each of these fish species were migratory as opposed to residents. Unlike 2021 and 2022, the Little Colorado River experienced large, prolonged floods during the spring of 2023. The detections from the spring window where the arrays were functional (i.e., February 15-June 4) detected unique PIT tags of 1407 bluehead sucker, 11 channel catfish, 21 common carp, 1724 flannelmouth sucker, 4114 humpback chub, and 91 individuals of unknown species.

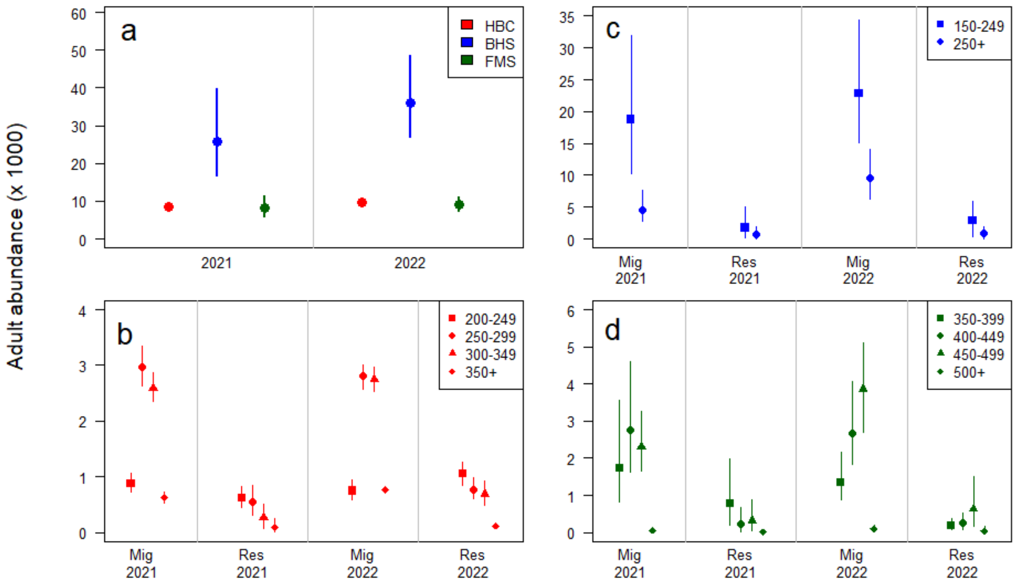

Figure G3. Abundances estimates of fishes in the Little Colorado River in spring of 2021 and 2022. Error bars for all plots refer to 95% credible intervals. Abundance estimates of adult humpback adult humpback chub (HBC; ≥200 mm total length), flannelmouth sucker (FMS; ≥350 mm fork length), and bluehead sucker (BHS; ≥150 mm fork length; a). Abundance estimates by size class (mm total length) and life history strategy (Mig = migrant, Res = resident) for humpback chub (b), bluehead sucker (c), and flannelmouth sucker (d). Provisional data, subject to change.

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

Science Questions/Hypotheses Addressed

- What are the long-term trends in relative abundance (catch per unit effort, CPUE) of HBC in the historical "aggregation" sites (Valdez and Ryel, 1995)?
- What is the abundance of HBC in western Grand Canyon?

Results

The results presented here include data through 2022, because main-stem aggregation data for 2023 is still in the process of being analyzed. HBC abundance increased in western Grand Canyon, beginning with spikes of age-0 HBC in 2014 that resulted in significant increases in the adult population the following years (Figure G4). The increase appears to have begun in the vicinity of the historical Pumpkin Spring aggregation (now often referred to as the JCM-west reach). By 2017, there was a substantial population of adult HBC present between Pumpkin Spring and Separation Canyon (~RM 210-240). Densities diminished downriver from Separation Canyon (below ~RM 240). Nevertheless, densities were still surprisingly high at some sites far downriver, such as at Columbine (~RM 273-275).

USFWS and USGS are working collaboratively on an abundance estimate for humpback chub in western Grand Canyon.

Additionally, we conducted opportunistic seining in 2022. We seined 52 backwaters between RM 1.7 and 246.34. Fish captures included 2,540 fish, of which 161 were HBC. All HBC measured (n = 112) were age-0 between 30-75 mm TL. Humpback chub sampled from backwaters while seining indicated some areas of higher catch below the 30-Mile aggregation (RM 36-42), the Little Colorado River Inflow (RM 55-69), Stephen Aisle and Conquistador Aisle (RM 120-123), and between Lava Falls and 218 Mile (~RM 180-218). Eight nonnative species were captured (catch in parentheses): channel catfish (3), common carp (9), fathead minnow (913), green sunfish (2), plains killifish (561), rainbow trout (3), striped bass (1), and threadfin shad *Dorosoma petenense* (6).

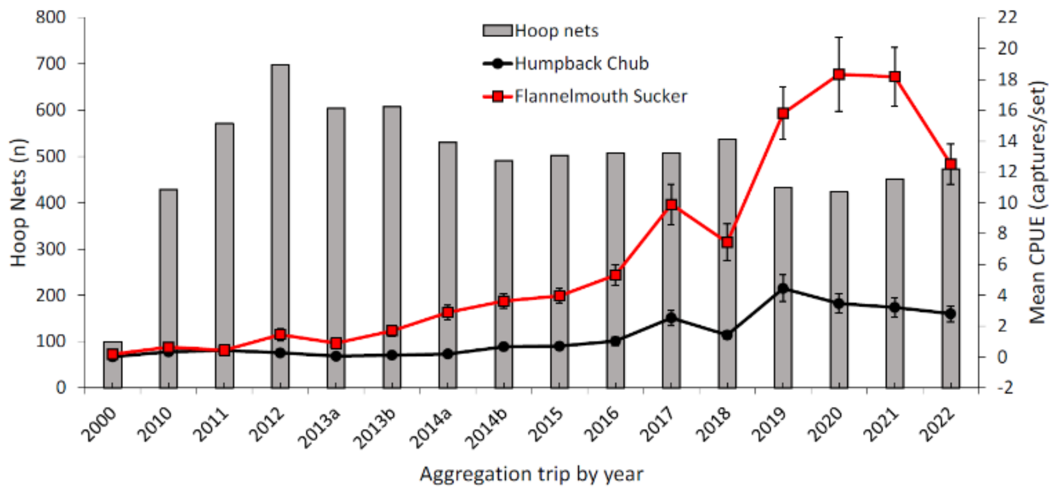

Figure G4. CPUEs of humpback chub *Gila cypha* and flannelmouth sucker *Catostomus latipinnis* (all size classes) paired with total hoop nets set for each Grand Canyon aggregation trip 2000, and 2010-2022. Note in 2013 and 2014, two hoop netting aggregation trips [July (a), and September (b)] were conducted. Provisional data, subject to change.

Element G.6. Juvenile Humpback Chub Monitoring – West

Science Questions/Hypotheses Addressed

- How do life history characteristics (e.g., survival, growth, reproduction, movement) differ between western Grand Canyon and Little Colorado River spawning HBC?
- What is the estimate of true (not apparent) survival for HBC in JCM-west?
- Are abundances in western Grand Canyon increasing, stable, or decreasing?

Results

The JCM-west reach was sampled three times (May, July, and October) in 2023 by USGS. JCM trips visited the JCM-west reach (RM: 210.5-214) after completing JCM-east sampling during the earlier portion of the trip. Sampling methods were the same for JCM-west and JCM-east reach (see Project Element G.3).

Species composition of catch in JCM-west was comprised mostly of native species, with the highest catch occurring for humpback chub (7257), flannelmouth sucker (5400), speckled dace (5213), and bluehead sucker (2202). Nonnative catch was comprised of fathead minnow (384), common carp (42), green sunfish (20), walleye (12), plains killifish (11), rainbow trout (11), gizzard shad (3), striped bass (2), and brown trout (2). In the JCM-west reach, catch of HBC >99 mm TL was 323 in May, 1472 in July, and 808 in October. In addition, the catch of HBC between 40-99 mm TL was 1582 in May, 865 in July, and 2201 in October.

Humpback chub population dynamics differ in JCM-west compared to Little Colorado River spawning humpback chub in that growth is relatively fast and adult survival relatively low in JCW-west compared to migratory HBC that spawn in the Little Colorado River (Dzul and others, 2023). Capture-recapture data from JCM-west will be used to update models and evaluate population trends in 2023. Emigration estimates from sonic-tagged HBC will be combined with apparent survival estimates for adults in JCM-west to obtain estimates of true survival.

Element G.7. Chute Falls Translocations

Science Questions/Hypotheses Addressed

The goal of this project, identified as a conservation tool (U.S. Department of the Interior, 2016), is to annually translocate at least 300 juvenile HBC from lower portions of the Little Colorado River to upstream of rkm 14.2 (i.e., upstream of Chute Falls) and to monitor these fish post-translocation.

- What is the abundance of HBC upstream of rkm 13.6 in the Little Colorado River?
- Are translocations an effective conservation tool for increasing abundance of adult HBC?

Results

Efforts to translocate HBC upstream of Chute Falls in the Little Colorado River have been ongoing since 2003. Translocations have been shown to be effective at increasing adult abundance of HBC (Yackulic and others, 2021). To date (as of 27 October 2023), approximately 5,044 juvenile HBC have been translocated upstream of Chute Falls. Of these, 173 were released above Chute Falls (at rkm 16.2) on 27 October 2023. No fish were collected for translocations into Havasu or Shinumo Creeks during the 2023 USFWS sampling trips in the Little Colorado River. In June 2023, it was estimated there were 1,254 HBC ≥100 mm (SE = 37) in the Atomizer reach (~rkm 13.6-14.1), of which 774 (SE = 24) were ≥200 mm (Figure G5). Likewise, it was estimated there were 537 HBC ≥100 mm (SE = 20) in the Chute Falls sample reach (~rkm 14.1-17.6), of which 518 (SE = 24) were ≥200 mm (Figure G5).

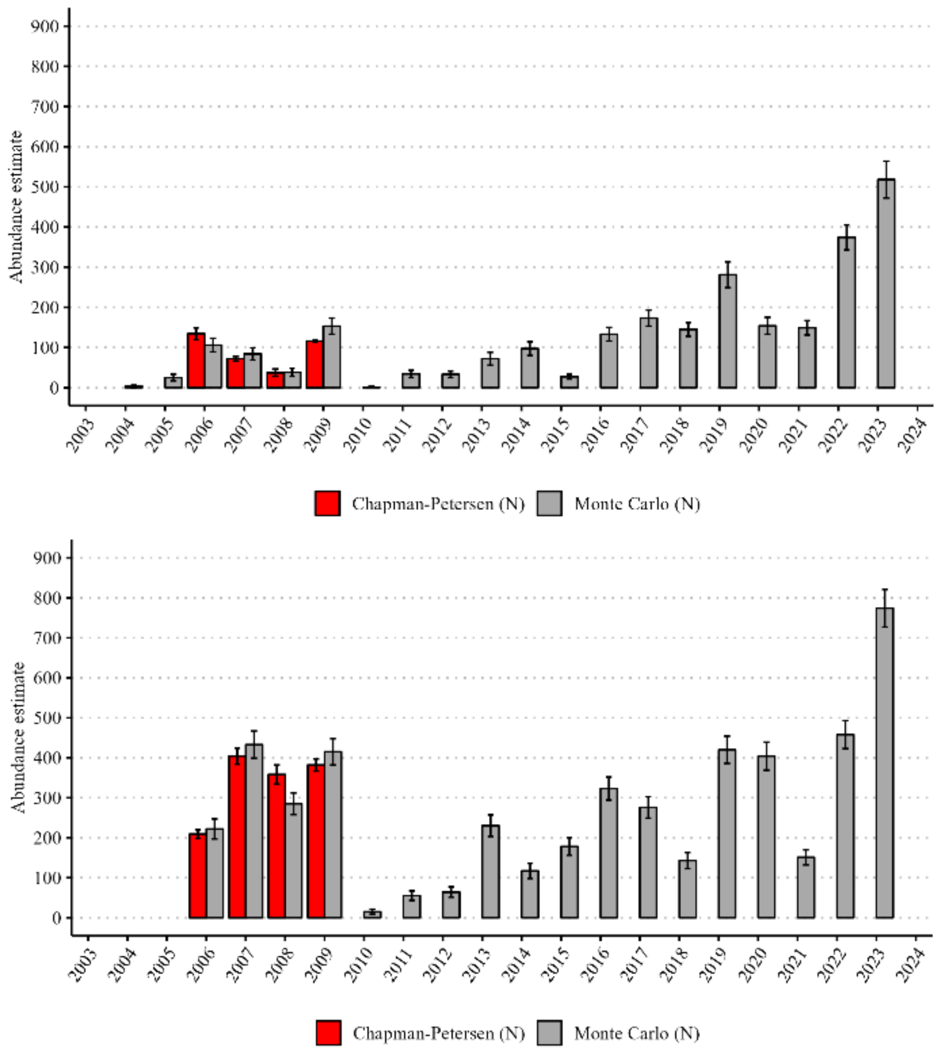

Figure G5. Abundances of adult humpback chub (≥ 200 mm TL) in the Chute Falls reach of the Little Colorado River (panel above) and in the Atomizer Reach (panel below) estimated with Chapman Petersen method (red bars), and Monte Carlo simulation (gray bars). Provisional data, subject to change.

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Yackulic, C.B., Van Haverbeke, D.R., Dzul, M.C., Bair, L.S., and Young, K.L., 2021, Assessing the population impacts and cost-effectiveness of a conservation translocation: Journal of Applied Ecology, v. 58, no. 8, p. 1602-1612, https://doi.org/10.1111/1365-2664.13908.

Project G Budget

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$328,681	$4,000	$51,900	$506,266	$0	$63,734	**$954,581**
Actual Spent	$288,754	$7,524	$42,976	$506,266	$0	$58,012	**$903,532**
(Over)/Under Budget	**$39,927**	**($3,524)**	**$8,924**	**$0**	**$0**	**$5,722**	**$51,049**

COMMENTS
FY23 Comments: - Underspent Salaries is due to HR-delays in filling positions and staff turnover. - Overspent in Travel & Training due to not budgeting costs associated with field work as travel. -Underspent Operating Expenses is due to the bulk purchase of PIT tags through BOR.

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

Presentations:

Dzul, M.C., Yackulic, C.B., and Kendall, W.L., 2023, Can “true” survival be estimated without global resights? It depends on “true” movement—presentation: Euring 2023 Analytical Meeting & Workshop, Montpellier, France, April 19, 2023.

Journal Articles:

Bonjour, S.M., Gido, K.B., McKinstry, M.C., Cathcart, C.N., Bogaard, M.R., Dzul, M.C., Healy, B.D., Hooley-Underwood, Z.E., Rogowski, D.L., and Yackulic, C.B., 2023, Migration timing and tributary use of spawning flannelmouth sucker (*Catostomus latipinnis*): Journal of Fish Biology, v. 103, no. 5, p. 1144-1162, https://doi.org/10.1111/jfb.15509.

Dibble, K.L., Yackulic, C.B., Bestgen, K.R., Gido, K.B., Jones, M.T., McKinstry, M.C., Osmundson, D., Ryden, D., and Schelly, R.C., 2023, Assessment of potential recovery viability for Colorado pikeminnow Ptychocheilus lucius in the Colorado River in Grand Canyon: Journal of Fish and Wildlife Management, v. 14, no. 1, p. 239–268, https://doi.org/10.3996/JFWM-22-031.

Dzul, M.C., Kendall, W.L., Yackulic, C.B., Van Haverbeke, D.R., Mackinnon, P., Young, K., Pillow, M., Rinker, P., and Thomas, J., *In Review,* Estimating migration timing and abundance in partial migratory systems by integrating continuous antenna detections with physical captures: Submitted to Journal of Animal Ecology.

Dzul, M.C., Yackulic, C.B., Giardina, M., Van Haverbeke, D.R., and Yard, M., 2023, Vital rates of a burgeoning population of humpback chub in western Grand Canyon: Transactions of the American Fisheries Society, v. 153, no. 4, p. 443-459, https://doi.org/10.1002/tafs.10415.

Dzul, M.C., Yackulic, C.B., and Kendall, W.L., *In Prep.,* Can "true" survival be estimated without global resights—It depends on "true" movement.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., 2023, Linking ecosystem processes to consumer growth rates—Gross primary productivity as a driver of freshwater fish somatic growth in a resource-limited river: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 9, p. 1456-1469, https://doi.org/10.1139/cjfas-2022-0229.

Van Haverbeke, D.R., Dzul, M.C., Yackulic, C.B., and Young, K.L., *In Prep*., Abundance estimation of a recent prodigious humpback chub population in western Grand Canyon.

USGS Data Releases:

Dzul, M.C., Yackulic, C.B., Giardina, M., Van Haverbeke, D.R., and Yard, M., 2023, Humpback chub (*Gila cypha*) capture histories and growth data for two areas in the Colorado River network from 2009-2022 and 2017-2022: U.S. Geological Survey data release, https://doi.org/10.5066/P9E96ADU.

Hansen, L.E., and Yackulic, C.B., 2023, Mark-recapture and environmental data used to predict flannelmouth sucker (*Catostomous latippinis*) growth rates within the Colorado River in the Grand Canyon from April 2012 to October 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9852I1G.

USFWS Reports:

Van Haverbeke, D.R., Newton, J., Young, K.L., Pillow, M.J., and Rinker, P.N., 2023a, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2022: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., U.S. Fish and Wildlife Service document no. USFWS-AZFWCO-FL-23-02, 53 p., https://www.fws.gov/sites/default/files/documents/Mark-Recapture%20and%20Fish%20Monitoring%20Activities%20in%20the%20Little.pdf.

Van Haverbeke, D.R., Rinker, P.N., and Pillow, M.J., 2023b, Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2022: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., U.S. Fish and Wildlife Service document no. USFWS-AZFWCO-23-05, 43 p.

Project H: Salmonid Research and Monitoring

Project Lead	Charles B. Yackulic	**Principal Investigator(s)** (PI)	Charles B. Yackulic, USGS, GCMRC Josh Korman, Ecometric Research David Rogowski, AZGFD Molly A.H. Webb, USFWS James A Crossman, BC Hydro
Email	cyackulic@usgs.gov		
Telephone	928-556-7379		

Goals and Objectives

This project is designed to evaluate the response of rainbow trout *(Oncorhynchus mykiss)* and brown trout *(Salmo trutta)* to experimental flows and broad-scale changes in environmental conditions, including water quality. Work done as part of this project informs our understanding of how fish populations in Lees Ferry respond to experimental flows outlined in the LTEMP including High-Flow Experiments (HFEs), equalization flows, and Macroinvertebrate Production Flows (Bug Flows), as well as other management actions like the incentivized harvest program to decrease Lees Ferry brown trout populations (Runge and others, 2018). Project H was divided into four Project Elements. Here, we report annual catch and community science data associated with trout monitoring in Glen Canyon (H.1), catch, fish condition and reproductive condition from the mark-recapture reaches in Lees Ferry (H.2), and ongoing population modeling (H.4) developed from data collected primarily through H.2. Brown trout early life stage survey results (H.3) were not planned for FY 2023 in the FY 2021-2023 Work Plan so we do not report on this element.

Project Elements

Element H.1. Rainbow Trout Monitoring in Glen Canyon (Arizona Game and Fish Department; AZGFD)

Research Objectives Addressed

The goal of this monitoring effort is to assess the status and trends of rainbow trout abundance and distribution in the Colorado River reach between Glen Canyon Dam and Lees Ferry, and to monitor angler use of the Lees Ferry fishery. We use three approaches to monitor the Lees Ferry trout fishery: 1) boat electrofishing, 2) angler surveys (creel) including the use of a game camera, and 3) a community science program with angling guides and private anglers that measure captured fish. We conduct boat electrofishing at randomly selected, 250-meter (m)-wide sites to obtain a representative sample of the fish assemblage within the Lees Ferry reach.

Our objectives are to gather long-term trend data on relative abundance using catch-per-unit-effort (CPUE) methods, population structure (size composition), distribution, growth rate, relative condition, and overall recruitment to reproductive size.

In addition, we conducted one night of sampling during summer and autumn sampling trips to detect warm-water nonnative species, results of which are reported in Project Element I.2. To estimate angler use, we conduct angler surveys to obtain a representative sample of the recreational angling community at Lees Ferry. Arizona Game and Fish Department (AZGFD) uses stratified random sampling to select a 6 days/month for interviews of both boat (access point creel at boat ramp) and shoreline anglers (roving creel).

Information obtained includes, but is not limited to, catch rates, gear type, species composition, harvest, and satisfaction with angling experience. Since June 2015, a game camera has been installed at Lees Ferry to record images of the boat launch area and provide a better estimate of boat anglers for the days and hours when a technician is not present. The community science program is an attempt to quantify the lengths of fishes captured by anglers. Length-related angler catch metrics are included in the Lees Ferry fisheries management plan but cannot be determined from angler surveys.

Results

Electrofishing

AZGFD completed three monitoring trips in 2023, sampling 118 sites and capturing 1,758 fishes including 953 rainbow trout, 449 brown Trout, 168 green sunfish (*Lepomis cyanellus*), 151 flannelmouth sucker (*Castostomus latipinnis*, 21 smallmouth bass (*Micropterus dolomieu*), seven bluegill (*Lepomis macrochirus*), six common carp (*Cyprinus carpio*), and three walleye (*Sander vitreus*). Rainbow trout CPUE (0.81 fish/minute [0.69, 0.93] was similar to 2022 (0.87 fish/minute [0.75, 0.98]) and continues to be the lowest we have observed since monitoring began in 1991 (Figure H1). Rainbow trout comprised 54.2% of our catch in 2023, the lowest relative proportion observed since sampling began in 1991 (Figure H2).

Historically (1991-2013) the assemblage was dominated (97-99%) by rainbow trout; however, in 2015 brown trout started increasing in numbers and contributed up to 25% of the fish assemblage. Beginning in 2022 we have been documenting an increase in nonnative warm-water fishes. Green sunfish comprised 9.6% of our total catch in 2023. Brown trout CPUE (0.38 fish/minute [0.32, 0.44]) was similar to 2022 (0.37 fish/minute [0.30, 0.44]). In our autumn monitoring, green sunfish compromised 18% of the catch, while rainbow trout comprised only 49% of the catch.

Angler Surveys (Creel)

Between January and early November of 2023, we conducted angler surveys on 61 days and interviewed 605 boat anglers and 117 walk-in anglers.

Angler catches rates (CPUE) for rainbow trout in 2023 for boat anglers was 0.66 [0.59, 0.73] fish/hour, and for walk-in anglers it was 0.40 [0.24, 0.57] fish/hour. Angler catch rates are below the AZGFD management goal for an angler catch rate of ≥ one rainbow trout per hour. Seventy two percent of boat anglers and 36% of walk-in anglers caught at least one fish.

Despite the low catch rates angler satisfaction (on a scale of 1-5) remained similar for walk-in anglers in 2023 (3.1 [2.7, 3.4]) compared to 2022 (3.3 [3.0, 3.6]). Boat angler satisfaction was similar in 2023 (3.9 [3.8, 4.0]) to 2022 (3.8 [3.7, 3.9]). In 2023, 75% of anglers interviewed were aware of the incentivized harvest program, and of those 45% said they would participate. Only 120 of 722 anglers interviewed captured a brown trout, and 82 (68%) of those anglers harvested a brown trout.

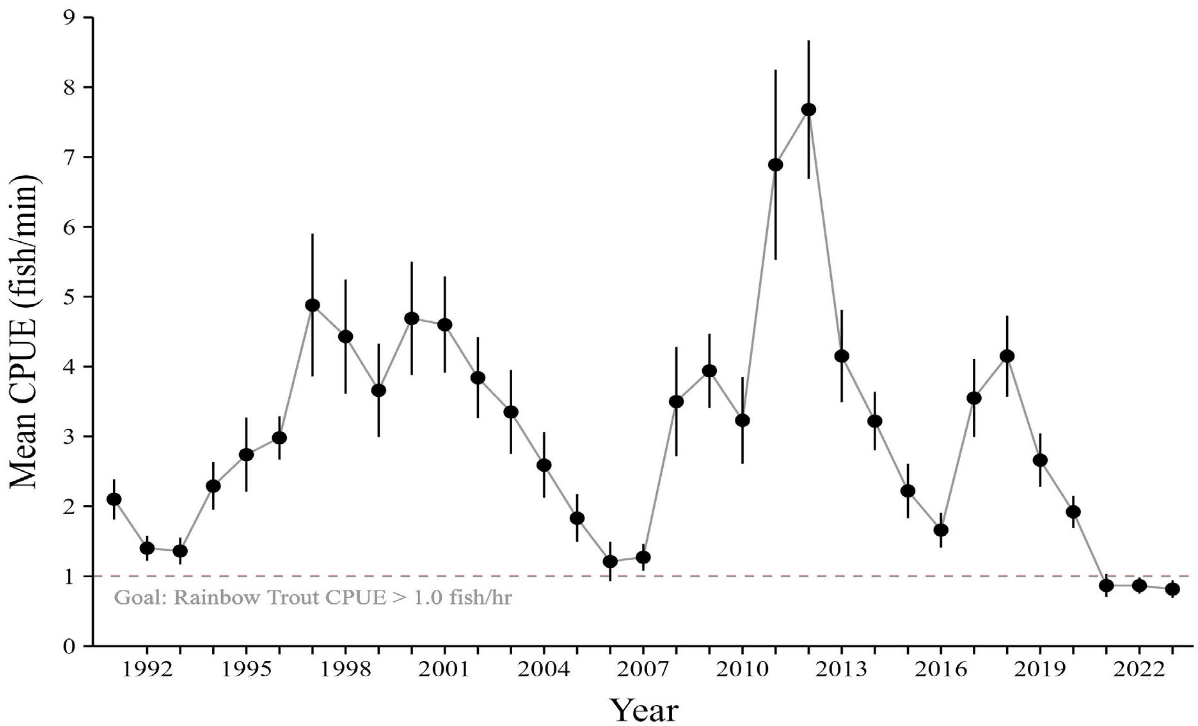

Figure H1. Average catch per unit effort (fish/minute) of rainbow trout at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing).

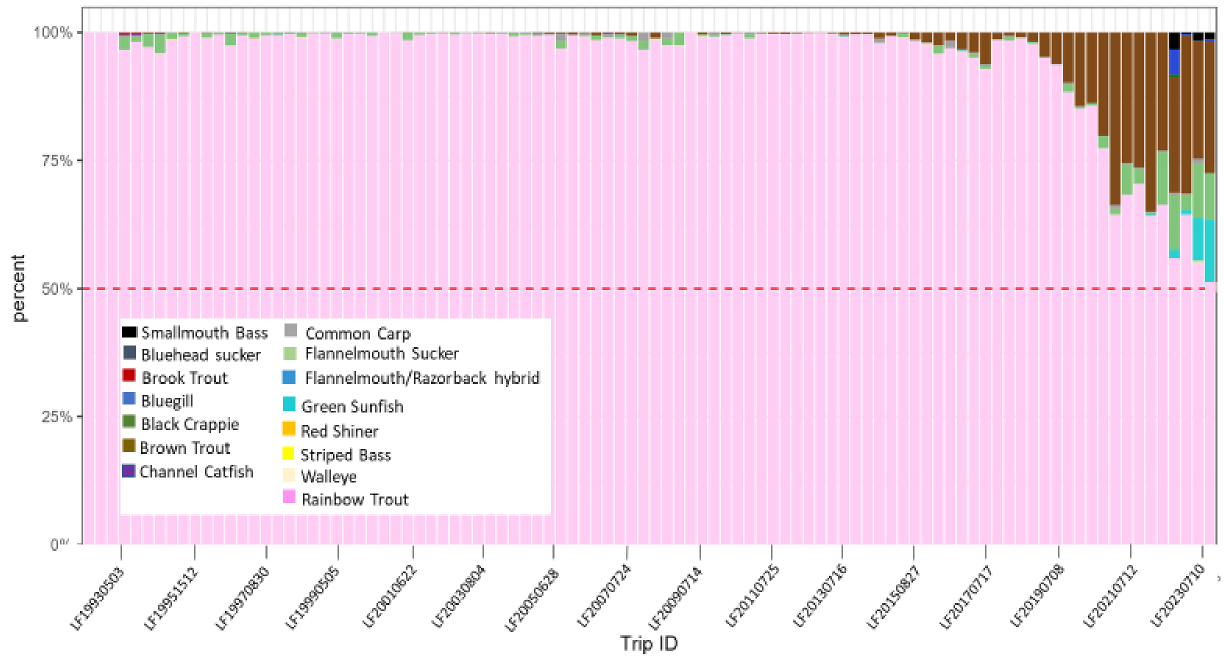

Figure H2. Fish assemblage at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing) by year.

Community Science Program

Between January and September of 2023, citizen scientists submitted length data on 715 rainbow trout and 18 brown trout. These data came from six private anglers with a total of 88 unique trips. These data are not representative of all anglers, as 82% of the angler trips were from one angler. Much fewer brown trout were captured in 2023 (n=18) compared to last year when 90 were captured. This may have been a result of fewer brown trout in the reach or our participating anglers were not targeting brown trout as much as last year. Rainbow trout captured by citizen scientists had a mean total length of 13.5 inches [13.4, 14.9] (343 mm [340, 379]), and brown trout had a mean total length of 16.2 inches [15.3, 18] (410 mm [389, 457]). Rainbow trout captured in 2023 were on average larger than those captured in 2022 (13.2 inches [13.2, 13.3] (337 mm [334, 339]). Based on citizen science data, the rainbow trout fishery at Lees Ferry was not meeting management goals (3a) for quality size fish; only 35% of angler trips resulted in anglers catching ten 14" Rainbow Trout in a 10-hour day (based on CPUE), and no Rainbow Trout 20" or greater were caught (out of 88 trips).

Element H.2. Experimental Flow Assessment of Trout Recruitment (TRGD Project)

Research Objectives Addressed

Element H.2 is designed to evaluate the response of rainbow trout and brown trout to Glen Canyon Dam operations, and to broad scale changes in environmental conditions, including water quality.

Work done as part of this project informs our understanding of how fish populations in Lees Ferry respond to experimental flows outlined in the LTEMP, including HFEs, equalization flows, and Macroinvertebrate Production Flows (Bug Flows), as well as other management actions like the incentivized harvest program to reduce the abundance of the Lees Ferry brown trout population (Runge and others, 2018). The project provides mark-recapture data that are integrated in open population and growth models to estimate vital rates, such as survival, recruitment (young of year), and growth, to better determine the cause for changes in rainbow and brown trout populations in Glen Canyon over time (Figure H3).

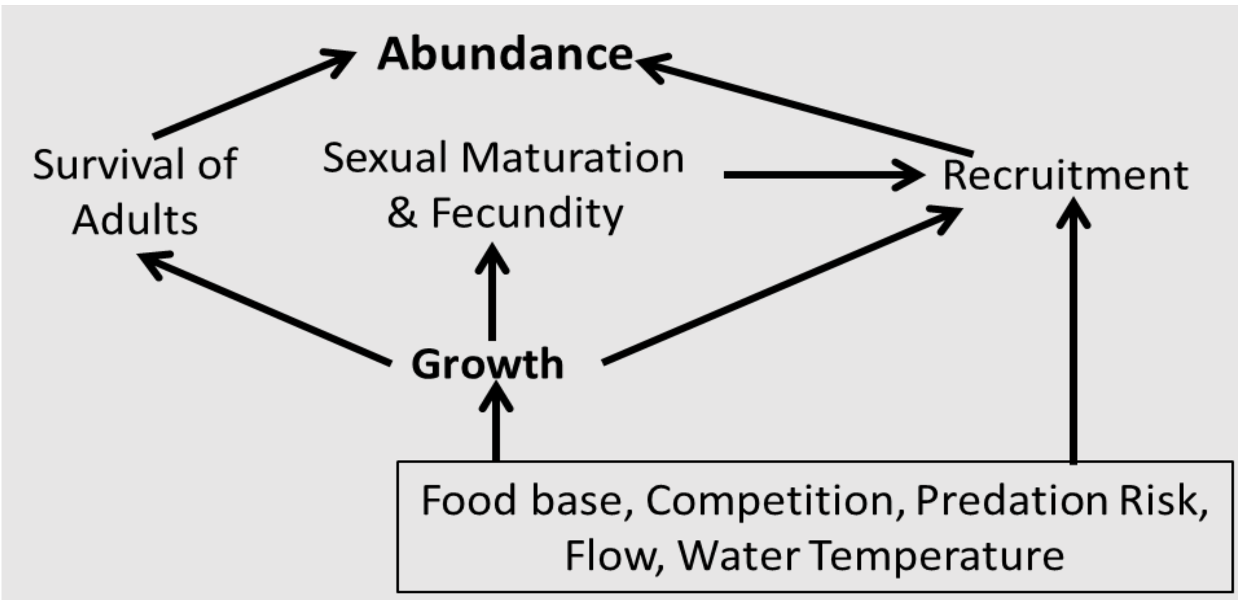

Figure H3. Conceptual model of how growth and other vital rates (survival, recruitment) influence abundance of rainbow and brown trout populations in Glen Canyon. This Project Element has linked factors such as prey availability, flow, and water temperature to vital rates, thus providing stronger inferences about cause-effect relationships between dam operations and other factors on population trends and status.

Results

TRGD Sampling in Lees Ferry

In 2023, two 3 km-long sub-reaches (1A and 1C) were sampled in February, April, and September (November data pending), and subreach 1C was also sampled in June. A total of 8,144 fishes (rainbow trout [4,786]; brown trout [1,591]; flannelmouth sucker [678]; green sunfish [967]; smallmouth bass [37]; bluegill sunfish [45]; common carp [33], black crappie (*Pomoxis nigromaculatus*) [2]; bluehead sucker [3], striped bass [1], and walleye [1]) were captured by electrofishing on trips up to and including the September trip. Rainbow trout catch remained low in 2023 and there has not been a substantive recruitment since 2017. Brown trout catch in 2023 was similar to the previous year. Catch rates of young of year in 2023 and 2022 were considerably lower than in 2020 and 2021.

Catch rates of green sunfish have increased substantially in recent years. In reach 1A, CPUE was near zero until the September 2022 trip (6.7 fish/km) and increased 8-fold by the September 2023 trip (52.3 fish/km). In reach 1C, CPUE was also near zero until the September 2022 trip (1 fish/km) and increased 12-fold by the September 2023 trip (12.3 fish/km). Larger GSF (75-124 mm) made up a higher proportion of the catch of the September 2023 trip.

Past research has shown that changes in the condition (plumpness as determined by length-weight characteristics) of rainbow trout often precede population declines (Korman and others, 2016, 2017, 2020). Condition of rainbow trout has been surprisingly high and stable considering elevated water temperatures and low dissolved oxygen levels in the summer and fall of 2022 and 2023 (Figure H4). Condition declined during intervals with higher water temperatures and low dissolved oxygen concentrations. The decline in condition of larger brown trout was particularly acute and occurred during months with normal water quality.

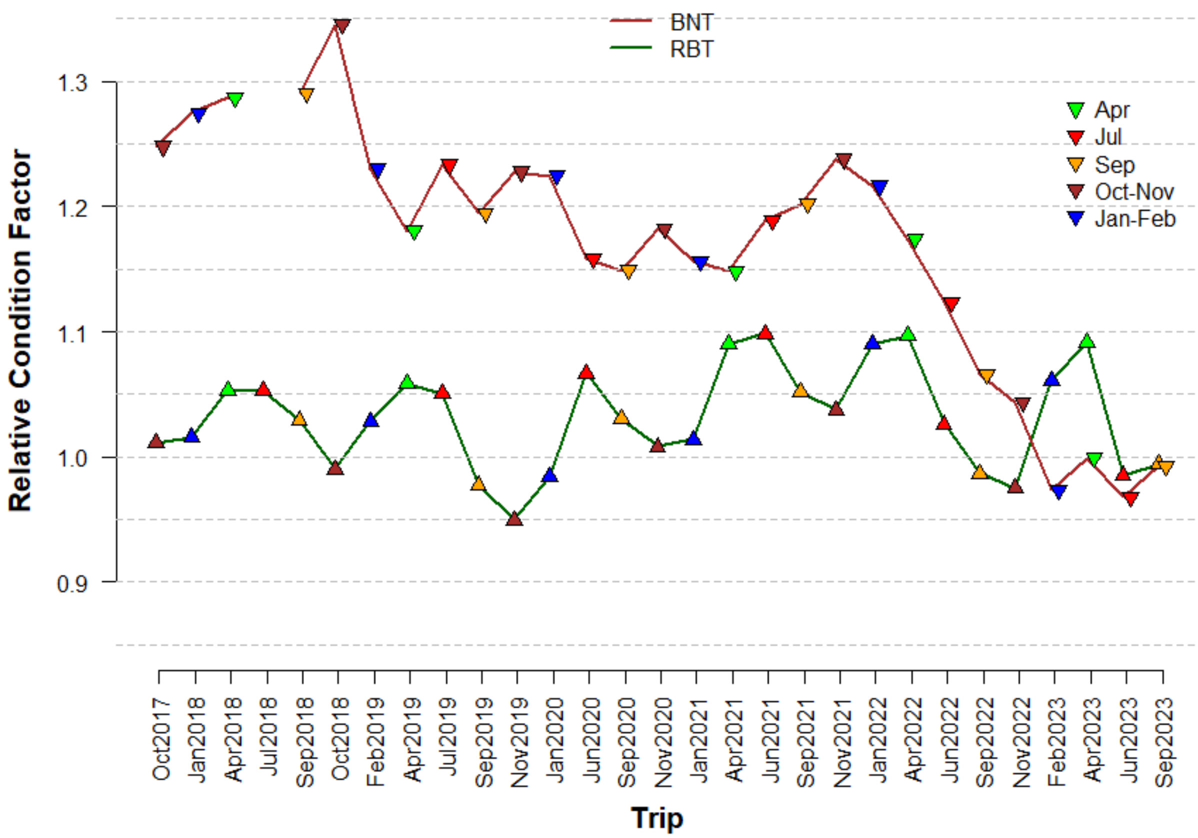

Figure H4. Relative condition factor for rainbow trout (lower, green line) and brown trout (upper, brown line) from electrofishing data collected in Glen Canyon, between September 2015 and September 2022 for fish with a fork length of 275 mm or greater. Points show the median values. Note that relative condition factor for both brown trout and rainbow trout is calculated using the length-weight equation for rainbow trout, for comparison purposes. Overall higher condition factor for brown trout indicates they are heavier per unit length than rainbow trout. Provisional data, subject to change.

We speculate that higher levels of competition and lower density of young of year rainbow trout have led to reduced prey intake for larger brown trout, which in turn has led to reduced growth rates and poor condition. These trends may be the cause for recent declines in brown trout recruitment. The population of brown trout in Glen Canyon may be transitioning into a lower abundance state that is in equilibrium with the available prey supply. Analysis of rainbow and brown trout capture-recapture data under this project and project H.4 will occur over the next few months and will be presented at the annual reporting meeting in January 2024.

Reproductive Condition Research

Condition factor of rainbow trout in the fall is a good predictor of sexual maturation rates the following winter and spring (Yard and Korman, 2020; Crossman and others, 2022, Figure H5). Condition factor is higher when growth is higher, potentially leading to an increase in the proportion of trout that reach sexual maturity and spawn. Understanding the relationship between condition-affected sexual maturation and recruitment may help us develop a more reliable method for forecasting and responding to small or large recruitment events. Current methods to evaluate sexual maturity in the field are relatively crude, relying on estimates of the proportion of fish that express gametes when they are squeezed. This approach is known to lead to a substantial bias in sex ratios (i.e., males express gametes more readily than females), and it is uncertain whether the percentage of males or females expressing gametes each year is proportional to the actual percentage of adults that spawn and contribute to recruitment.

In the FY 2018-20 TWP we conducted a detailed study to quantify season-, size-, and sex-specific variation in rainbow trout population reproductive structure based on histological analyses of gonad tissue. A secondary objective was to use the histological assignment of reproductive stage to determine the accuracy of nonlethal methods (manual expression and ultrasonography) for assigning sex. This work was published (Crossman and others, 2022) and found that some of the larger male trout that should be in reproductive condition are not, and overall, a surprisingly large proportion of adult trout are not in reproductive condition. Rates of atresia (degeneration of ovarian follicles) in females was highest in the fall. We suspect these patterns in rainbow trout were the result of low growth rates due to limited prey availability and elevated water temperatures. Correct sex assignment using ultrasonography was significantly higher for rainbows in spawning condition compared to immature fish and reproductive females (100% accuracy) had higher accuracy than males (77%).

Objectives of the rainbow trout reproductive work started in FY 2018-20 TWP were then expanded to brown trout in FY 2021-22 with the goal of comparing reproductive structure between the two species using histology and further expanding the application of ultrasonography to understand the accuracy in assigning reproductive condition to the spawning population of each species.

Preliminary results from histology showed higher proportions of spawning capable brown trout in November and January compared to rainbow trout which were spawning from November through April. However, a small portion (~20%) of brown trout were identified to be in spawning condition during the April trip, which was later than previously suspected. As found in rainbow trout, a number of large (>400 mm) brown trout that should be in reproductive condition were not, a result which could be related to the declining condition in the population in the last few years (Figure H4). Ultrasonography was demonstrated as a highly effective tool to assess reproductive structure of both trout species, for individuals greater than 275 mm. Application of ultrasonography has been extremely successful with >99% (n=1,116) and >94% (n=684) of trout >275 mm scanned and assigned to a reproductive condition (specific reproductive stage for females) on the November 2022 and February 2023 trips, respectively.

From the preliminary ultrasound data, rates of atresia appear to be higher in rainbow trout compared to brown trout in fall 2022, despite declining condition in both species (Figure H4). Work to compare the population reproductive structure between the two species from fall 2021 through winter 2023 is ongoing and will be completed in winter 2024. Given continued decline in brown trout condition through 2023, a comprehensive assessment of reproductive structure using ultrasonography is planned for fall and winter 2023-2024 to further define the relationship between condition and the proportion of spawning capable fish. Describing the variation in reproductive potential will not only improve our ability to forecast recruitment but will also describe temporal and spatial overlap of spawn timing between the two species and potential competitive interactions. Future work could apply these methods to understand reproductive dynamics of humpback chub and other native fishes.

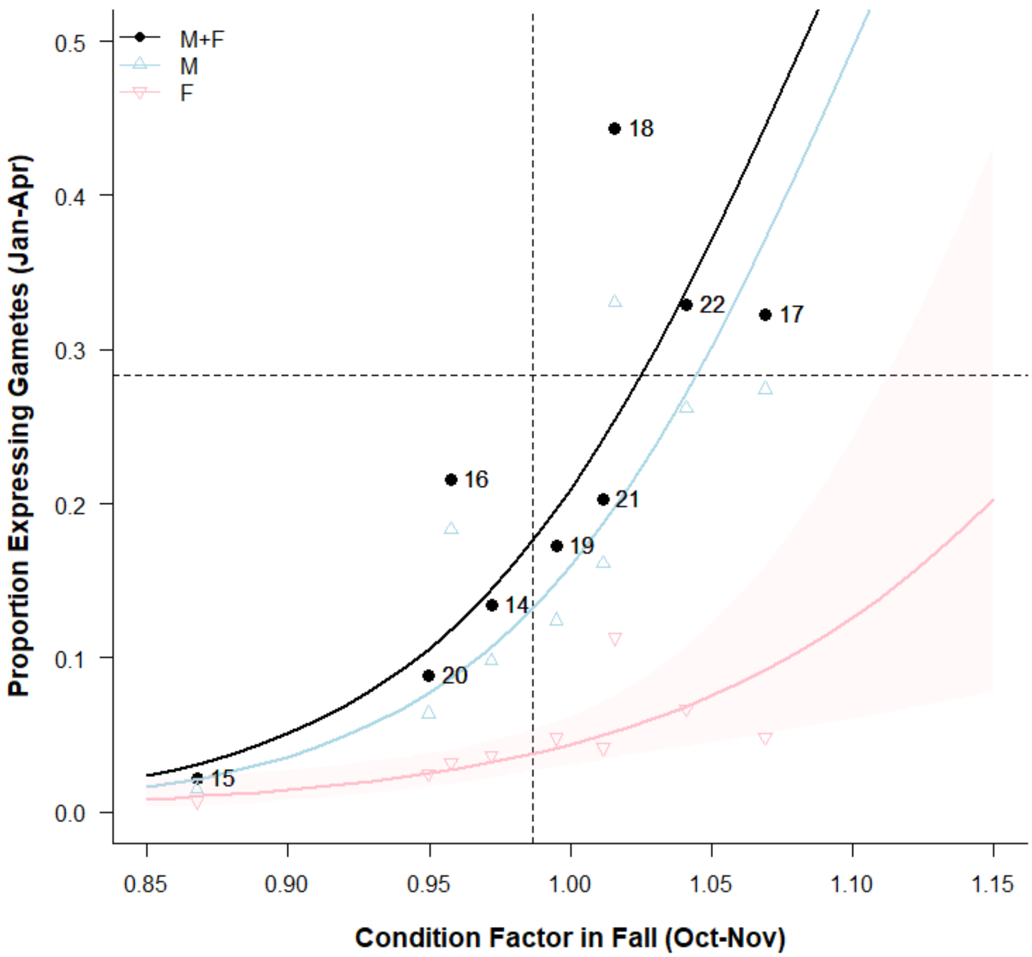

Figure H5. Proportion of rainbow trout ≥250 mm that expressed gametes during January and April trips, predicted as a function of condition factor during the previous fall. The year beside each data point shows the year of spawning (January and April trips).

Outmigration from Lees Ferry

The abundance and persistence of rainbow trout near the Little Colorado River depends on both the numbers of juvenile trout that disperse from Glen Canyon, and their subsequent survival and reproduction rates in Marble Canyon (Korman and others, 2016). Previous research has indicated it is likely that small trout move downstream and repopulate Marble Canyon during years when the Lees Ferry fishery has large recruitment (Yard and others, 2016; Korman and Yard, 2017; Korman and others, 2021, Figure H6). In 2022 we continued monitoring young-of-year (YOY, or less than one-year-old) trout populations in Marble Canyon and the Little Colorado River by conducting sampling in association with the April, July, and October JCM trips (Project Element G.3). These data will be used to further understand dispersal dynamics relative to experimental flows, fish density, and water quality.

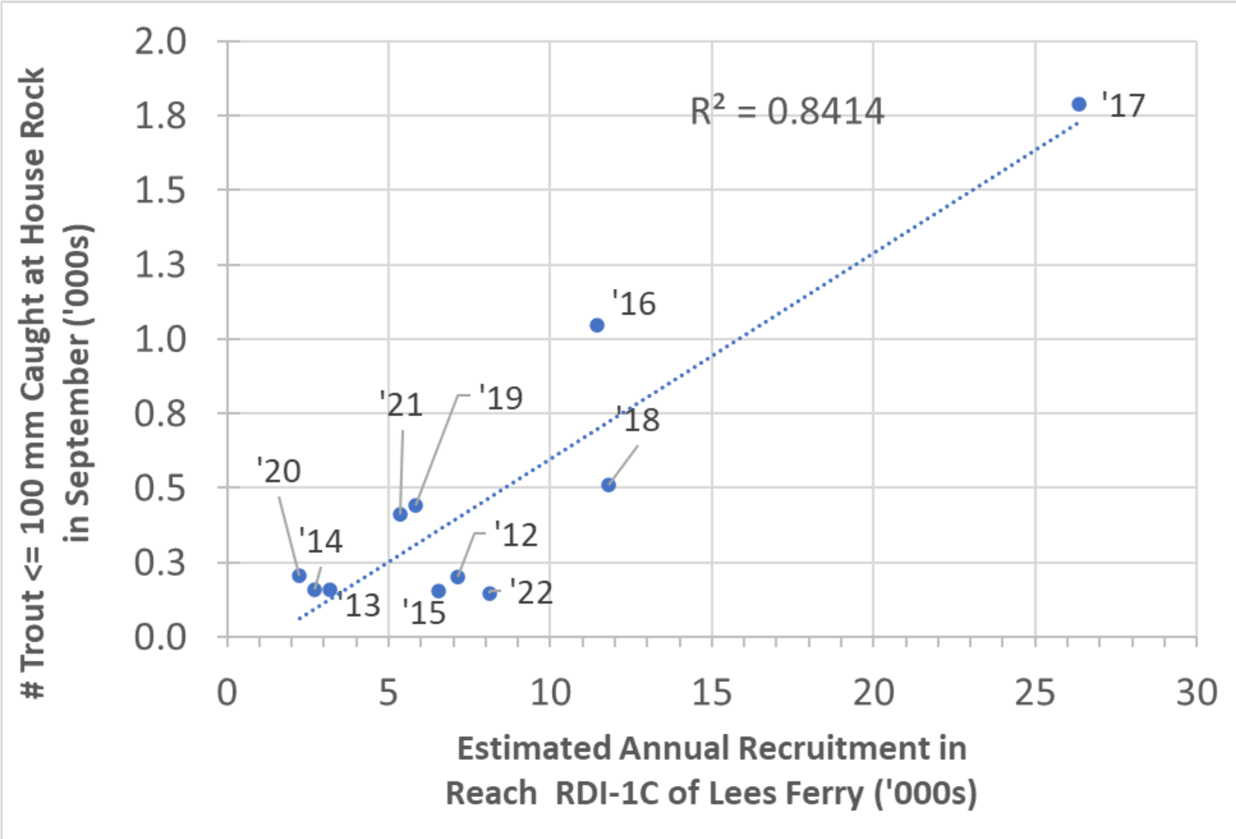

Figure H6. Relationship between estimated annual recruitment of rainbow trout to the smallest size class (75-124 mm) in reach RDI-1C in Lees Ferry and 1st pass catch of young of year rainbow trout (trout with forklengths ≤ 100 mm) in the House Rock reach in upper Marble Canyon on the September trips.

Element H.4. Salmonid Modeling

Science Questions/Hypotheses Addressed

The goal of this element is to analyze field data on salmonid populations collected in Project Elements H.1, H.2, and G.3 to estimate the efficacy of ongoing management actions and improve our capacity for predicting impacts of future management actions. Specifically, we identify four areas of research in this work plan: 1) reassess the causal hypotheses explored in Runge and others (2018) using data collected in recent years, 2) estimate the efficacy of incentivized harvest of brown trout by modifying the existing brown trout model to incorporate harvest data to inform managers and improve design of incentives (Project J), 3) estimate population dynamics of rainbow trout in the Lees Ferry reach in response to experimental flows and other drivers, and 4) continue development of a simple integrated model to predict recruitment and outmigration of rainbow trout using multiple data sources over nearly a 20-year period.

Results

Modeling in all four areas of research progressed but was slowed by the requests to divert staff attention to smallmouth bass issues and an overall lack of fisheries staff. In 2023, we published two manuscripts accepted in 2022 that address brown trout movement in response to the use of a weir in Bright Angel Creek and fall HFEs (Healy and others, 2023) and simulate potential response of brown trout to different management and climate change scenarios (Healy and others, 2023). In addition, two modeling manuscripts focused on rainbow trout dynamics were published in 2023 after acceptance in late 2022.

The first manuscript estimated the impacts of both fall HFEs and bug flows on rainbow trout growth and contrasted the effects sizes of these designer flows with the expected impacts of declining reservoir levels (Korman and others, 2023). The second manuscript, developed in conjunction with Project E, integrated rainbow trout growth and abundance data with invertebrate drift data collected through Project F to estimate prey production in Lees Ferry and show it was tightly linked to change in soluble reactive phosphorous concentrations in Lees Ferry (Yard and others, 2023). In FY 2023, we implemented simulation studies to test the bias and precision of a new approach for integrating mark-recapture and catch data that we are also applying to better understand rainbow trout population dynamics throughout Marble Canyon. Results from the rainbow trout and brown trout models will be reported at the January 2023 reporting meeting as usual but were not available in time for this report.

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Project H Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$147,413	$500	$24,066	$148,000	$0	$26,149	**$346,128**
Actual Spent	$109,795	$4,602	$90,474	$88,000	$0	$28,501	**$321,372**
(Over)/Under Budget	**$37,618**	**($4,102)**	**($66,408)**	**$60,000**	**$0**	**($2,352)**	**$24,756**

COMMENTS

FY23 Comments:
-Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Overspent in Travel & Training due to not budgeting costs associated with field work as travel.
- Overspent in Operating Expenses is due to change in funding mechanism for a cooperator from a Cooperative Agreement to a contract.
-Underspent amount in Cooperative Agreement is due to not funding a cooperative agreement and using staff to complete work.

Project H Deliverables: Salmonid Research and Monitoring

Presentations:

Yackulic, C.B., 2023, The times, They are a-changin'—Fish and the Grand Canyon: River Guides Training Seminar, Marble Canyon, Ariz.
Yackulic, C.B., Eppehimer D., Korman J., Giardina M., Yard M., Mihalevich B., Deemer B., Tennant L., and Schmidt, J., 2023, The Lees Ferry tailwater—Water quality, trout, and an uncertain future—virtual presentation: 14th Annual Native and Wild Trout Conference Phoenix, Ariz.
Yackulic, C.B., Saracco, J., Korman, J. and Dzul, M., 2023, Sharing abundance—Integrating long-

term count data with short-term capture-recapture data in a marginalized, multistate Jolly-Seber framework—presentation: Euring Analytical Meeting, Montpellier, France.

Journal Articles:

Healy, B., Budy, P., Yackulic, C., Murphy, B.P., Schelly, R.C., and McKinstry, M.C., 2022, Exploring metapopulation-scale suppression alternatives for a global invader in a river network experiencing climate change: Conservation Biology, v. 37, no. 1, e13993, p. 1-18, https://doi.org/10.1111/cobi.13993.

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USGS Data Releases:

Korman, J., Yard, M., and Deemer, B.R., 2023, Rainbow trout growth data and growth covariate data from Glen Canyon, Colorado River, Arizona, 2012-2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9XU3SQP.

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

Project Lead	Charles B. Yackulic (acting)	**Principal Investigator(s)** (PI)	Charles B. Yackulic, USGS, GCMRC Eric Frye, USGS, GCMRC David Ward, AZGFD (formerly with USGS, GCMRC) David Rogowski, AZGFD Drew Eppehimer, USGS, GCMRC Kimberly Dibble, NPS (formerly with USGS, GCMRC)
Email	cyackulic@usgs.gov		
Telephone	928-556-7379		

Goals and Objectives

This project continues long-term, standardized monitoring conducted by the Arizona Game and Fish Department (AZGFD) throughout the Colorado River from Lees Ferry (River Mile (RM) 0) to Pearce Ferry (RM 281) for the combined purposes of tracking the status of native fishes as well as identifying new invasive aquatic species (system-wide native fishes and aquatic invasive species monitoring). This project also provides detection capability for new warm-water invasive fishes, which may be entering the Colorado River ecosystem (CRe) from Lake Powell by passing through Glen Canyon Dam, descending tributaries such as the Little Colorado River or swimming upstream from Lake Mead (improve early detection of warm-water invasive fishes). Nonnative fishes typically have detrimental impacts on the stability of native fish communities (Marsh and Pacey, 2005; Erős and others, 2020). Identifying sources of warm-water invasive fishes in the Colorado River ecosystem (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).

In addition, this project quantifies the potential negative impacts of nonnative fishes and fish parasites on native fish populations both in the field by collecting diet and abundance information as well as in the laboratory by quantifying predation risk of nonnative fishes in replicated laboratory trials (assess the risks warm-water nonnative fishes pose to native fishes). In response to increasing focus on the ongoing invasion of nonnative smallmouth bass *(Micropterus dolomieu)* and various GCDAMP Adaptive Management Work Group (AMWG) directives, there has also been increasing focus on developing models to guide evaluation of management actions under this project, as well as shifts in the focus of laboratory studies to focus on the role of turbidity in age-0 smallmouth bass growth and survival.

Project Elements

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

Research Objectives Addressed

The primary goal of the system-wide monitoring program (Element I.1 of this project) is to monitor the status and trends of native and nonnative fishes in the Colorado River from Lees Ferry to Lake Mead. The AZGFD randomly samples selected reaches and sites throughout the Colorado River in Grand Canyon using boat electrofishing, baited hoop nets, and angling to obtain a representative sample of the fish assemblage. Species composition and relative abundance (catch-per-unit effort (CPUE)) are used to interpret trends in relative abundance and distribution of native and nonnative fishes throughout the Grand Canyon.

Trends in CPUE over time for system-wide native and nonnative fishes are calculated by examining deviations in the mean catch among years, compared with the calculated 95% confidence interval of catch rate for a given year. Although CPUE trends can be biased if capture probability is not consistent, consecutive years of catch rates above or below the 95% confidence interval of the mean could indicate a significant trend, especially if trends do not coincide in the environmental conditions that typically impact capture probability (e.g., turbidity, temperature, etc.). Additionally, because of the broad nature of our sampling (i.e., multispecies, geographically broad), we are also able to use our monitoring data to provide information related to emerging management concerns or questions.

Results

AZGFD completed spring monitoring trips (April and May) and one autumn sampling trip in 2023. Turbidity during the April trip (April 1 – 14, RM 0 - 281) was high downstream of the Little Colorado River, so we reduced the number of electrofishing sites, conducted no electrofishing downstream of RM 174.21 and increased the number of hoop nets set downstream of the Little Colorado River.

On the April trip we sampled 71 electrofishing sites, set 140 baited hoop nets and angled at 13 sites. We captured 564 fish at electrofishing sites, 1043 fish in baited hoop nets, and 25 fish angling. During the May trip (May 12 – 26, RM 0 – 281), we captured 1461 fish at 188 electrofishing sites, 2223 fish in 127 baited hoop nets, and 67 fish across 14 angling sites. During the autumn sampling trip (October 31 – November 3) we sampled upstream of Pearce Ferry Rapid (RM 270 - 281.5). We captured 283 fish at 39 electrofishing sites, 214 fish in 36 hoop net sets, and no fish at three angling sites.

Over the 24 years of AZGFD monitoring, relative abundance of most nonnative fishes has decreased, and abundance of most native fishes has increased. We observed a substantial shift in the fish assemblage within Marble Canyon (RM 0 – 61.7) during our 2023 sampling.

While nonnative rainbow trout (*Oncorhynchus mykiss)* have dominated the fish assemblage in this reach in recent years (rainbow trout comprised 89.4% of the catch in this reach in 2022) we observed a large increase in native flannelmouth sucker (*Catostomus latipinnis*) catch rates with flannelmouth sucker making up 61.9% of our electrofishing catch in the Marble Canyon reach. By comparison, rainbow trout only comprised 34.2% of our electrofishing catch within Marble Canyon in 2023. Along with higher number of flannelmouth sucker in general, we noticed a substantial increase in the number of smaller flannelmouth sucker in the Marble Canyon reach compared to prior years (Figure I1).

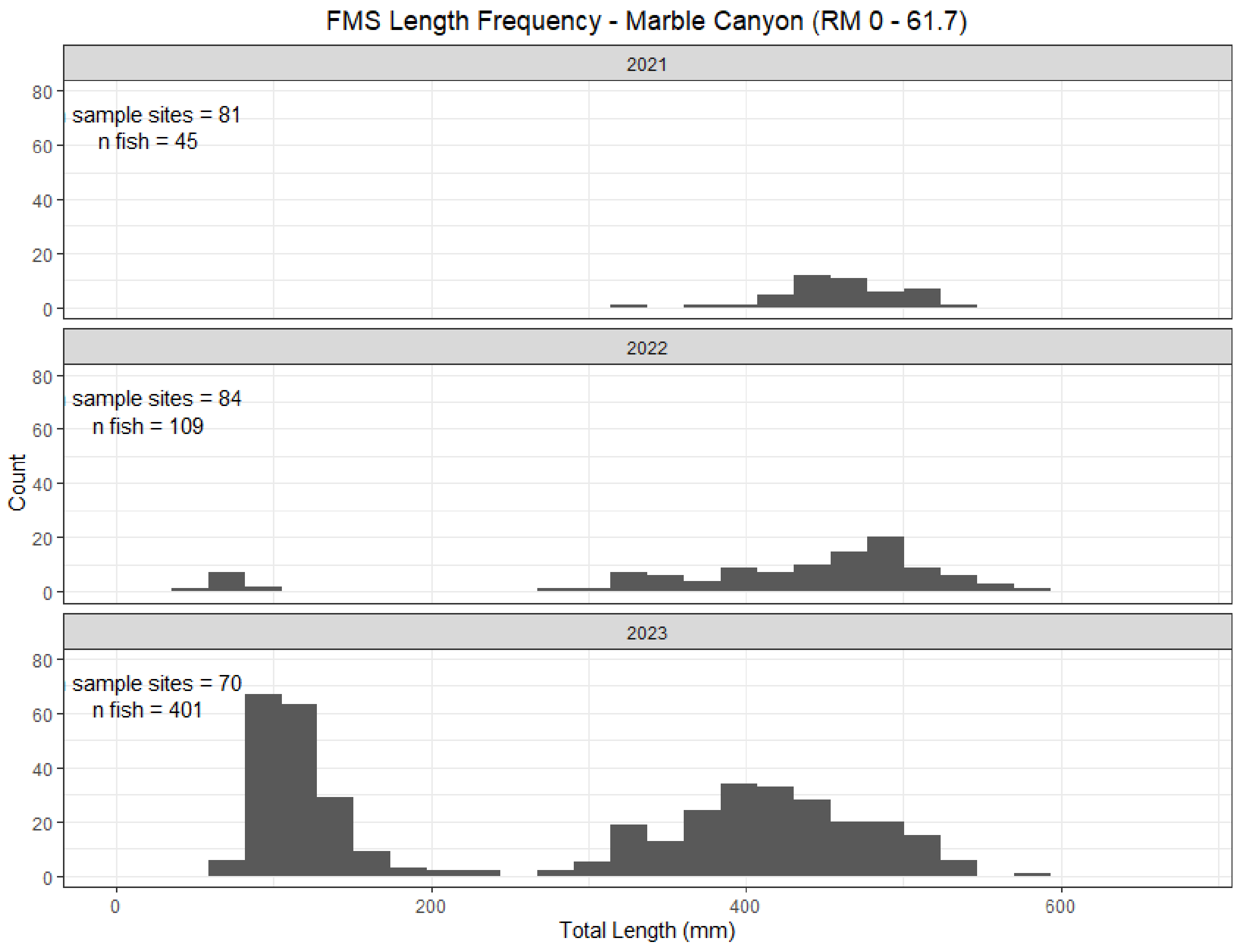

Figure I1. Length frequency histogram of flannelmouth sucker caught during AZGFD April downstream monitoring trips in 2021, 2022, and 2023. Graphs include data from both electrofishing and hoop net data. Number of sample sites and number of fish captured during each trip in Marble Canyon are shown on the left of the plots.

Results from hoop net sampling in 2023 were similar to results from the past three years (Figure I2). Flannelmouth sucker were the most common species captured in hoop nets (n = the 2719, 78.4% of total hoop net catch), followed by humpback chub (n = 693, 20.0% of total hoop net catch). We continue to see a higher CPUE of flannelmouth sucker in the Marble Canyon reach as well as Glen Canyon.

Each gear type has certain biases and targets different species. Angling was originally included in sampling to target nonnative channel catfish (*Ictalurus punctatus*), and in the past it has been a productive method of capturing channel catfish. In recent years channel catfish encounters during angling have been rare and no catfish were captured during angling this year. This was a relatively productive year for angling overall with 54 humpback chub (*Gila cypha*) being captured, of which 34 were untagged.

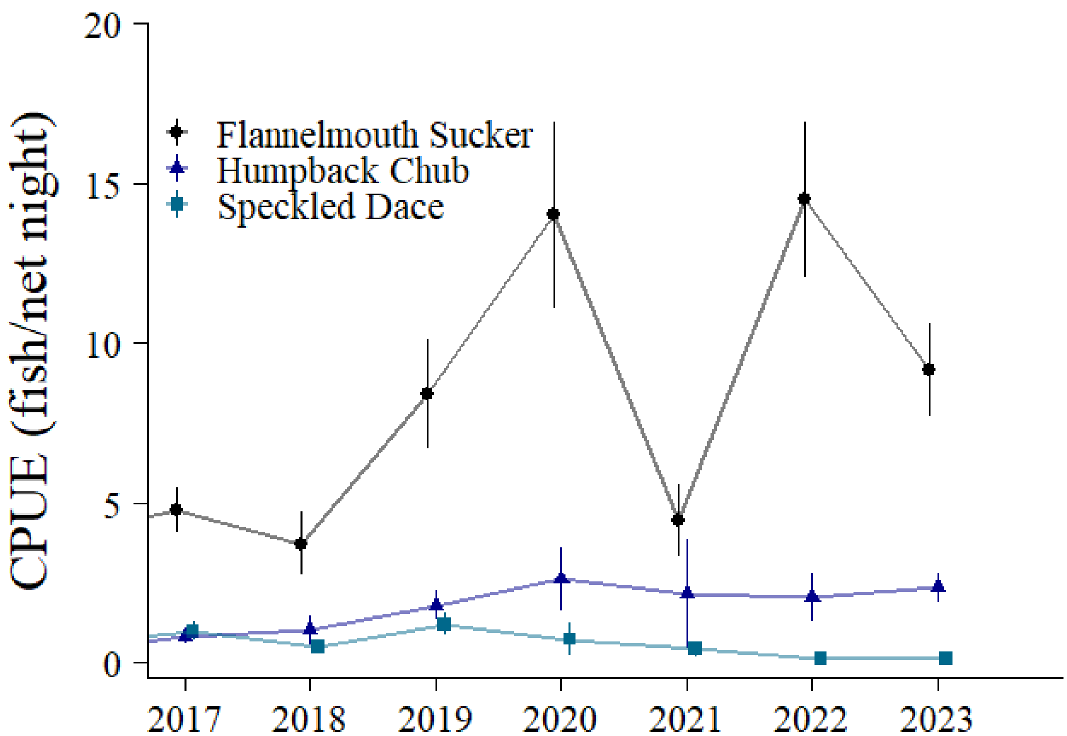

Figure I2. Catch per unit effort (fish/net night) with 95% CI of native fishes from baited hoop nets from the Arizona Game and Fish Department spring long-term monitoring of the Colorado River.

Rare nonnatives captured in the spring sampling included brown trout (*Salmo trutta;* n = 27 fish captured), common carp (*Cyprinus carpio*; n = 6), fathead minnow (*Pimephales promelas*; n = 10), green sunfish (*Lepomis cyanellus*; n = 3), striped bass (*Morone saxatilis;* n = 1), crayfish (*Procambarus clarkia; n* = 1), and walleye (*Sander vitreus*; n = 1). During autumn monitoring we captured two striped bass, 12 fathead minnow, one walleye, and one gizzard shad (*Dorosoma cepedianum)*.

Element I.2. Improve Early Detection of Warm-Water Invasive Fish

Science Questions

Element I.2. is focused on improving early detection of warm-water invasive fishes. To improve early detection of rare, nonnative species in Glen Canyon, AZGFD conducts rare nonnative monitoring twice a year (summer and autumn). The primary goal of the rare nonnative monitoring is to provide early detection of rare nonnative fish species in Glen Canyon. AZGFD targets areas where rare nonnatives have been caught before and warmer water areas such as spring inflows and sloughs/backwaters. In addition, GCMRC conducted an environmental DNA (eDNA) project in FY 2022. The objective of the eDNA project is to detect rare native and nonnative species by filtering eDNA from the water. Fish shed scales, mucous, and other tissue into the water, allowing researchers to collect eDNA via filtration to determine whether a species is present. Since the quantity of eDNA in a sample linearly scales with fish biomass, relative abundance metrics can be calculated using quantitative Polymerase Chain Reaction (PCR) and standard curves (Klymus and others, 2015). These efforts to improve early detection of invasive warm-water fishes will be used to direct future monitoring efforts or emergency responses as needed.

Results

AZGFD conducted summer (July 10 - 13) and fall (October 16 - 19) targeted monitoring of invasive warm-water species in Glen Canyon in areas where rare nonnatives have been caught before. These areas include the restricted area just below the dam, and in warmer water areas such as spring inflows, sloughs, and backwaters. In the fall of 2023, these efforts captured 3 bluegill (*Lepomis macrochirus)*, 44 green sunfish, and two smallmouth bass. We also encountered invasive nonnatives while sampling standardized monitoring sites in both summer and fall, including high numbers of green sunfish. During summer sampling we collected one bluegill, five common carp, 55 green sunfish, 10 smallmouth bass, and three walleyes. During fall sampling we collected five bluegill, 110 green sunfish, and 10 smallmouth bass. Analysis of eDNA samples taken in 2022 was slowed by loss of USGS staff in charge of this Project Element and delays in hiring replacements; however, this project will be a priority once USGS staff have been hired.

Element I.3. Assess the Risks Warm-Water Nonnative Fish Pose to Native Fish and forecast potential for invasion

Science Questions

The goal for Element I.3 of this project has been to evaluate the impacts of various invasive nonnative warm-water fishes on humpback chub in both laboratory and field settings. In particular, risks of predation on humpback chub by predators such as channel catfish, common carp, green sunfish, and smallmouth bass have recently been investigated in a laboratory setting.

In FY 2023, we focused on smallmouth bass as potential predators of humpback chub under both clear and turbid (300-500 NTU) conditions. For each replicate, 12 humpback chub (70 mm avg. TL) were exposed to 4 Smallmouth bass (150 mm avg. TL) for 24 hours after a 24-hour acclimation period, after which the number of surviving humpback chub were counted.

In FY 2023, we also conducted a pilot laboratory experiments to better understand how turbidity may impact the early life history of smallmouth bass. Although much has been studied about smallmouth bass population dynamics and control of these fish, there are still many questions remaining regarding age-0 fish, especially in the unique settings of large regulated, river systems. Disentangling potential mechanisms underlying the growth and survival of young fish is important because subtle variability in abiotic and biotic factors during these early stages may exert tenfold effects on fish recruitment and long-term population growth (Houde and Hoyt, 1987; Houde, 1989).

In FY 2023, we also worked on improving and applying a smallmouth bass model developed to forecast potential for smallmouth bass invasion of Lees Ferry and evaluate potential management responses. This model estimates the risk of smallmouth bass establishment based on thermal suitability under different hydrologic and management scenarios.

Results

Laboratory trials suggested that humpback chub exposed to smallmouth bass have a higher probability of survival in turbid conditions (50% survival) as compared to clear water conditions (30%). This lab study used three turbidity treatments (0,100,500 NTU) with two replicates each. Age-0 smallmouth bass were obtained from the Gavins Point National Fish Hatchery and the Genoa National Fish Hatchery. However, transportation mortality was high, and only 16 fish per treatment/replicate were able to be used. Daphnia zooplankton were cultivated in the lab and fed to the smallmouth bass, and the fish were measured every two weeks. The experiment ran from August 2, 2023, until September 29, 2023. Results were inconclusive due to small sample sizes; however, we plan a larger and more robust turbidity experiment for the coming summer.

The smallmouth bass model is currently being used to evaluate potential nonnative fish management alternatives for the LTEMP SEIS.

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Project I Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$220,574	$0	$7,100	$238,550	$0	$35,896	**$502,120**
Actual Spent	$264,539	$9,217	$66,235	$238,550	$0	$50,074	**$628,615**
(Over)/Under Budget	**($43,965)**	**($9,217)**	**($59,135)**	**$0**	**$0**	**($14,178)**	**($126,495)**

COMMENTS

FY23 Comments:
- Overspent salaries is due to position turnover and an added Smallmouth Bass river trip in Oct 2022 (FY23).
- Overspent in Travel & Training due to not budgeting costs associated with field work as travel and the added Smallmouth Bass river trip in Oct 2022 (FY23).
-Overspent funds in Operating Expenses is for purchases of necessary lab equipment and field supplies and includes logistics costs for the Smallmouth Bass river trip in Oct 2022 (FY23).

Project I Deliverables: Warm-Water Native and Nonnative Fish Research and Monitoring

Presentations:

Eppehimer, D.E., Yackulic, C.B., Bruckerhoff, L.A., Wang, J., Young, K.L., Bestgen, K.R., Mihalevich, B.A., and Schmidt, J.C., 2023, Drought, water storage, and an invasion—Designing responses to stop the spread of smallmouth bass in the Grand Canyon—presentation: American Fisheries Society, Grand Rapids, Mich., August 20-24, 2023.

Frye, E., and Ward, D.L., 2023, Common carp, uncommon predator—presentation: Colorado River Aquatic Biologists, Laughlin, Nev., January 4-5, 2023.

Frye, E., and Ward, D.L., 2023, Common carp, uncommon predator—presentation: Desert Fishes Council, St. George, Utah, November 16-20, 2023.

Ward, D.L., and Frye, E., 2023, Removal of invasive aquatic species using dissolved oxygen manipulation—presentation: Phoenix, Ariz., November 1, 2023.

Journal Articles:

Eppehimer, D.E., Yackulic, C.B., Bruckerhoff, L.A., Wang, J., Young, K.L., Bestgen, K.R., Mihalevich, B.A., and Schmidt, J.C., *In Review*, Failure to store—Low reservoir elevations spread non-native fish by increasing water temperature and propagule pressure: Submitted to Fisheries.

Project J: Socioeconomic Research in the Colorado River Ecosystem

Project Lead	Lucas Bair	**Funded Principal Investigator(s)** (PI)	Lucas Bair, USGS, GCMRC Joshua Abbott, ASU
Email	lbair@usgs.gov		
Telephone	(928) 556-7362		

Goals and Objectives

In the GCDAMP TWP FY 2021-23, Project J is integrating economic information with data from long-term and ongoing physical and biological monitoring and research studies led by the USGS Grand Canyon Monitoring and Research Center (GCMRC). This integration is leading to the development of tools for scenario analysis that improve the ability of the GCDAMP to evaluate and prioritize management actions, monitoring, and research. In addition, Project J includes monitoring and research efforts to better understand recreational behavior related to the brown trout *(Salmo trutta)* incentivized harvest program and recreational preferences for trip attributes (e.g., flows) that allow for inference into how recreational values are influenced by Glen Canyon Dam operations.

Project J's primary goal in the GCDAMP TWP FY 2021-23 is to address the humpback chub *(Gila cypha)* hydropower and energy, sediment, and recreational experience LTEMP FEIS resource goals. This is accomplished by addressing the LTEMP Record of Decision (U.S. Department of the Interior, 2016a, b) objective to "determine the appropriate experimental framework that allows for a range of programs and actions, including ongoing and necessary research, monitoring, studies, and management actions in keeping with the adaptive management process."

Project Elements

Element J.1. Predictive Models for Adaptive Management

Science Question:

- What is the optimal combination of flow (e.g., Trout Management Flows (TMFs)) and non-flow actions that improve and support the long-term stability of downstream resources (e.g., humpback chub, sediment) while also maintaining or improving the value of hydropower generation at Glen Canyon Dam?

Results:

- Preliminary results indicated that TMFs are viable (effective and economically efficient) rainbow trout control measures to achieve humpback chub abundance goals only when rainbow trout recruitment in Lees Ferry is high, humpback chub aggregation abundance is low, and rainbow trout abundance in Marble Canyon and the Juvenile Chub Monitoring (JCM) reach is high. This baseline result is based on the estimated economic cost of TMFs (see Project N) relative to rainbow trout removal cost and the effectiveness of TMFs specified in the LTMEP EIS (U.S. Department of the Interior, 2016b). See the FY 2021 GCMRC Annual Report for additional details related to preliminary results.

- Updated results indicate that learning to improve management, by conducting TMFs during low recruitment years, is not a cost-effective approach to managing the system. If TMFs are used to manage more problematic species, such as brown trout, leading to the viability of humpback chub being a more consistent concern, then learning by implementing TMFs on a more frequent basis, even if not immediately required to manage brown trout populations, does become cost-effective.

In FY 2023, GCMRC and cooperators continued the development of a sediment-hydropower predictive model that addresses the sediment, hydropower and energy, and recreational experience goals. This model uses a sandbar model developed by Mueller and Grams (2021) and a sand transport model developed by Wright and others (2010), the hydropower optimization model in Project N, and the ongoing research related to recreational boating in Grand Canyon (Neher and others, 2019). This Project Element is also integrated with the systems modeling taking place in Project O.11. Both Project J.1 and O.11 will assist in the identification of optimal monthly release volumes with respect to the sediment and hydropower goals. This is important given current low water conditions, where the monthly allocation of volume and timing of high-flow events maybe more critical to balance resource tradeoffs.

This project subcomponent aligns with the August 2022 GCDAMP Adaptive Management Work Group (AMWG) directive to evaluate High-Flow Experiments under low-elevations in Lake Powell and subsequent annual low-flows. The model will allow for the evaluation of the frequency, flow, and duration of HFEs that would be effective while also considering other objectives such as hydropower. See the GCDAMP TWP FY 2021-23 for additional detail.

Element J.2.

Science Question:

- How does brown trout monetary harvest incentives impact the number of angler trips, targeting behavior, and retention rates at Lees Ferry?

Results:

- We find evidence that this program was unsuccessful at drawing significant additional fishing effort (in daily trips) into the fishery. However, a select number of high performing anglers caught and retained a significant number of brown trout in late 2022 and early 2023 (Figure J2). The incentive was reduced to its base level, $33 per fish, in April 2023. We hypothesis that this resulted in a decline in angler effort. Additional data and in-depth angler interviews will allow us to test this hypothesis.

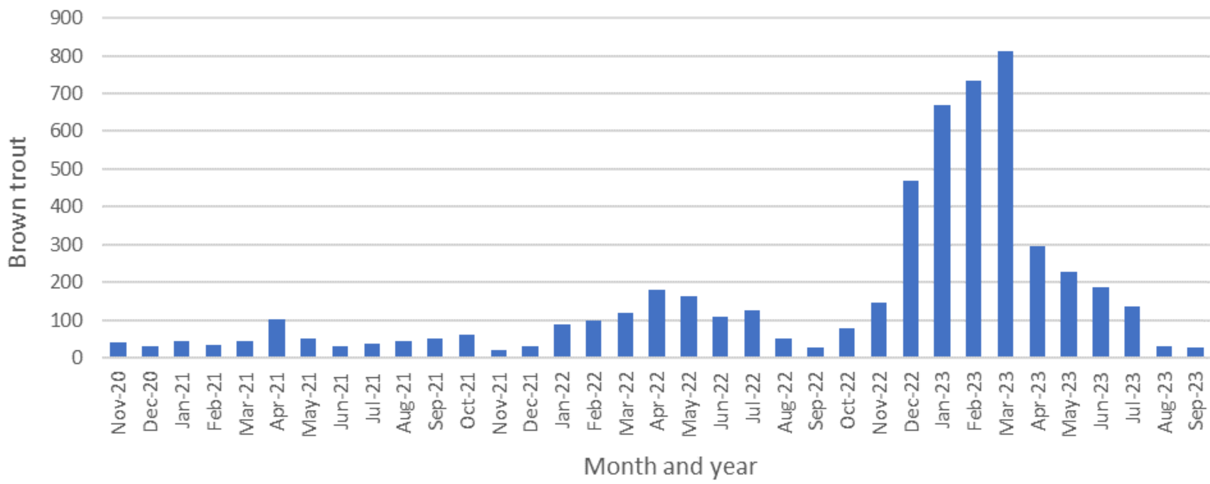

Figure J1. Monthly brown trout harvest as part of the brown trout incentivized harvest program.

The primary objective of this Project Element is to evaluate how structure of monetary payout from the incentivized harvest program influences participation, harvest, and retention rates within the brown trout fishery at Lees Ferry. Understanding these program outcomes and underlying behavioral factors will inform approaches to meet removal objectives.

In FY 2023, GCRMC and Arizona State University (ASU) collaborators closely coordinated with the NPS on incentive design for the program. GCMRC and ASU will continue to advise the NPS on incentive structure and program design in FY 2024.

Angler surveys in FY 2022 allowed GCMRC and ASU researchers to obtain name and address information of anglers to utilize in a follow-up mail survey. The follow-up mail survey will provide a more in-depth evaluation of the incentive structure and angler participation of the brown trout incentive program. GCMRC and ASU researchers received approval through the Office of Management and Budget review as part of the Paperwork Reduction Act (Public Law, 1995) in June 2023. The survey has gone through several iterations of expert review and focus groups and pretesting occurred in November 2023 in Scottsdale, Flagstaff, and Page, Arizona. The survey is being implemented in December 2023.

The survey will be distributed to over 600 anglers. The survey will also include in-person interviews with the highest performing anglers, those who have caught over 50 brown trout. This information will provide insight into level of effort required to become successful in the program, the impact of the incentive structure on participation, and the overall cost-effectiveness of the program relative to other removal methods.

As background, potential Lees Ferry anglers face a certain number of choices per-year in which they can decide either to take a Lees Ferry fishing trip or to do something else. Conditional on choosing to take the trip, anglers can choose how long to fish, where to fish, and what gear to use—all of which impact the number of rainbow or brown trout that they catch on that trip. Finally, the angler chooses the percent of rainbow and brown trout caught to retain rather than releasing. The product of these three decision variables — trips-taken, catch per trip, and retention rate — is the total number of rainbow or brown trout that an angler lands, or harvests, in a year (see Figure J2).

We use daily angler-level data on fishing behavior and outcomes from the Arizona Game and Fish Department Lees Ferry creel survey (January 2016 – December 2022) to estimate the impact of the program on brown trout landings, as well as the three behavioral variables (trips, catch-per-trip, and retention rate) that comprise landings (Figure J2). We use these data to investigate any potential program-induced changes in trip counts, catch rates (number of rainbow or brown trout caught by an angler on a given day), and retention rates (percent of caught rainbow or brown trout that each angler retained). The creel technician also records each angler's gender, age, and home zip codes, the number of fishing trips they have taken to Lees Ferry that year, how many hours they spent fishing that day, the type(s) of fishing gear they used (fly, spin, or both), and which species (rainbow trout, brown trout, or both) they were targeting. We use this information, including hours fished and gear use, to help explain how and why catch rates changed after the program was implemented.

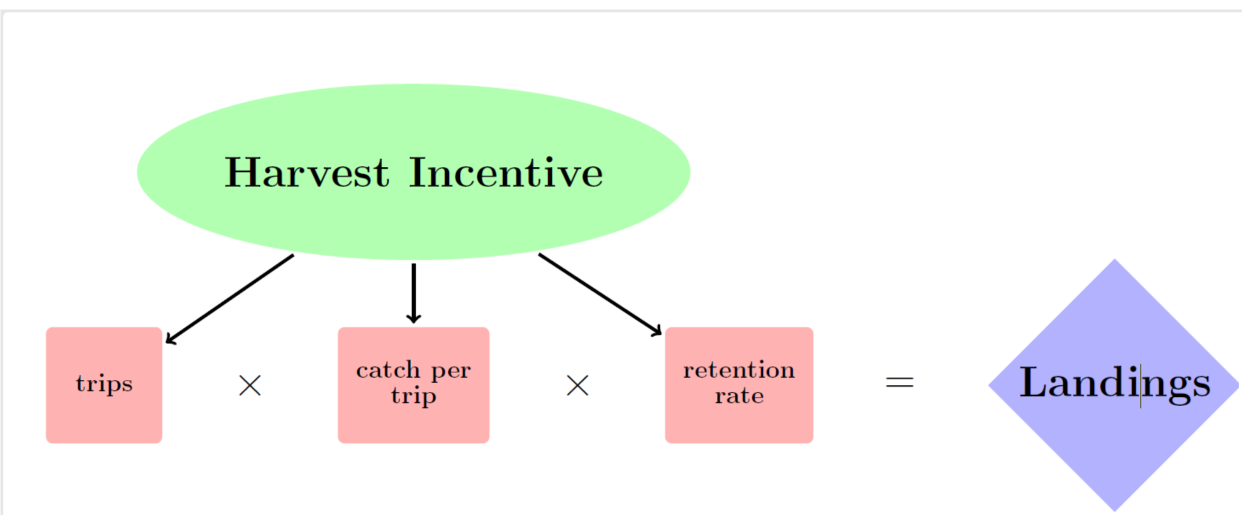

Figure J2. The factors over which a program incentive may increase brown trout harvests.

We estimate five separate models in order to investigate the direct impact of the program on brown trout harvest, as well as any indirect effects of the program on rainbow trout harvest. Our models estimate the program's impact on trip-taking, as well as on brown trout and rainbow trout catch-per-trip and retention rates amongst unguided boat anglers.

Because guided anglers largely do not participate in the program, we assume they are untreated and drop their data from our estimations to avoid biasing our results. The models control for season, hydrology, weather, and COVID-19 impacts. We have updated the model in FY 2023 with June 2021 thought December 2022 program results.

Our updated preliminary results suggest that the Lees Ferry Incentivized Harvest Program failed to bring additional angling effort (i.e., daily trips) into the fishery in general, likely due to how remote and costly it is to access the fishery. However, with additional data we have more confidence in the impact of bonanzas, or fishing tournaments, scheduled at Lees Ferry. These events increased trip taking and this increase led to an increase in rainbow trout catch and retention during these events. However, brown trout catch was negatively impacted by the bonanzas. This preliminary result is likely due to an increase in anglers new to Lees Ferry, unfamiliar with locations of and methods used to catch brown trout.

No general increase in trips and a drop in rainbow trout catch rates due to the program suggests that anglers changed their targeting behavior (i.e., where they fished, what gear they used, etc.) in response to the program treatment. We plan to further investigate this hypothesis by assessing how catch-contributing behaviors (i.e., gear use, hours fished) changed post-treatment to look for possible mechanisms to explain this post-treatment drop-in rainbow trout catch rates.

We now find, with the updated models, that the program had a positive effect on brown trout retention rates and the implementation of the 3rd fish bonus ($50 incentive for every third fish) increased brown trout catch rates. Note, the pit tag reward ($300 for every pit tag) was implemented one month after the 3rd fish incentive, and the overall increase in brown trout catch is hypothesized to be part of an overall incentive increase. We will explore this relationship between incentives and angler catch further and assess how retention rates may have changed according to angler type to identify potential mechanisms driving these results.

The limited success of the program is due to a small number of very successful anglers. Our in-person survey of high performing anglers in December and January 2023 will provide insight into their process of learning to successfully participate in the program and the effect of incentive on their behavior. The results of these anglers are very different than the results of the average Lees Ferry angler, presented above.

Element J.3. Recreation Monitoring and Research

The objective of this Project Element is to further refine our understanding of recreational preferences for specific flow attributes as controlled by operations at Glen Canyon Dam and within the flow parameters of the LTEMP ROD (U.S. Department of the Interior, 2016b). No funded research was conducted in FY 2023.

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

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Project J Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$126,530	$3,000	$1,500	$24,500	$0	$17,275	**$172,805**
Actual Spent	$103,013	$4,076	$36,474	$25,000	$0	$18,872	**$187,435**
(Over)/Under Budget	**$23,517**	**($1,076)**	**($34,974)**	**($500)**	**$0**	**($1,597)**	**($14,630)**

COMMENTS
FY23 Comments: - Underspent Salaries is due to change in mechanism for completing work with cooperators and contractors instead of salaried employees. - Overspent Travel & Training is due to rescheduled meetings and conferences post Covid-19. - Overspent funds in Cooperative Agreement is due to change in mechanism for completing work with cooperators and contractors.

Project J Deliverables: Socioeconomic Research in the Colorado River Ecosystem

Presentations:

Bair, L., 2022, Adaptive management of regulated rivers—Eliciting indigenous knowledge and perspectives to inform monitoring and research—presentation: ACES session on knowledge and value pluralism, ACES: A Community on Ecosystem Services, Washington D.C., December 2022.

Bair, L., 2022, Panel chair, NEPA—Multiple Knowledge Systems: Plural ES Values & Environmental Justice ACES, A Community on Ecosystem Services, Washington D.C., December 2022.

Bair, L., 2022, Results of a Navajo Nation survey—Managing Glen Canyon Dam and the Colorado River in Grand Canyon—presentation: Navajo Nation Historic Preservation Department. November 2022, Window Rock, Ariz.

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., and Bair. L.S., *In Prep*., The economic cost of designer flows in river conservation.

Hoelting, K.R., Martinez, D.E., Bair, L.S., Schuster, R.M., and Gavin, M.C., 2023, An opportunities framework for improved integration of cultural-benefits-knowledge in environmental decision-making: published on SocArXiv preprint server, submitted to Ecology and Society, https://doi.org/10.31235/osf.io/v6fxs.

Jungers, B., Abbott, J.K., and Bair, L.S., *In Prep*., Program evaluation of the Lees Ferry Brown Trout Incentivized Harvest Program.

Loomis, J.B., and Bair, L.S., 2023, Recreation use values for water-based recreation: Oxford Research Encyclopedia of Environmental Science, p. 1-35, https://doi.org/10.1093/acrefore/9780199389414.013.797.

Project K: Geospatial Science and Technology

Project Lead	Thomas Gushue	**Principal Investigator(s)** (PI)	Thomas Gushue, USGS, GCMRC Caitlin Andrews, USGS, GCMRC Erica Byerley, USGS, GCMRC Joseph Thomas, USGS, GCMRC
Email	tgushue@usgs.gov		
Telephone	(928) 556-7370		

Summary, Goals and Objectives

The Geospatial Science and Technology project (Project K) provides support to USGS Grand Canyon Monitoring and Research Center (GCMRC) science projects in the areas of Geographic Information Systems (GIS) expertise, database development and operation, programming and source control for code development, web application development, and other tasks for producing online data resources. The scope of support provided by this project encompasses application of enterprise-scale relational databases, use of standard source control platforms for managing programming code and software/application development, migration of project data away from flat files and into enterprise database systems, and providing consultation for projects on possible migration of data resources into the USGS' Cloud Hosting Solutions (CHS) environment within Amazon Web Services (AWS) cloud platform, or other suitable endpoints.

Most work performed within Project K falls within one of three main categories, presented as Project Elements in the Triennial Work Plan — Geospatial Data Analysis, Geospatial Data Management, and Access to Geospatial Data Holdings and Online Data Resources. Many of the efforts put forth through this project will have aspects that can be discussed in all three of these categories as there is often overlap from one category to another. The approach Project K has employed for these Project Elements has had two underlying threads: 1) support the overall Center needs through the development of systems and resources, building capacity and expertise along the way, and 2) support science projects with specific tasks that align with modernizing and improving upon each project's data management, analysis, and data access strategies, usually by leveraging newer technologies to achieve these goals.

Project Elements

Element K.1. Geospatial Data Analysis: Support to Science Projects

GIS Administration

Work performed for this Project Element is designed to support research and monitoring projects from the FY 2021-2023 Triennial Workplan 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 GIS tool development and support.

Often this work involved the oversight and supervision of science project staff with various GIS-related tasks including spatial analysis in support of projects, training for staff and cooperators in GIS data entry and database management concepts, data processing techniques, production of printed maps and online map products, error troubleshooting, and other basic GIS methods and techniques.

GIS Administration tasks related to Center-wide support included the testing and migration of systems to newer versions of the most commonly used GIS/Remote Sensing software, maintaining licensing information and working with SBSC IT staff to ensure all licenses, software, extensions, add-ons, and custom applications work properly. This work includes the installation, configuration, and administration of ESRI Desktop ArcGIS and Enterprise GIS software for GCMRC (ESRI, 2020a). Additionally, this project is responsible for handling data calls pertaining to a wide array of GCMRC's data resources every year.

GIS Support to Projects

In FY 2023, Project K continued to maintain and expand on its use of the open-source PostgreSQL relational database platform for storing, maintaining, and serving GCMRC's enterprise geospatial data sets. Data sets currently hosted include past and recent remote sensing overflight imagery, topography and bathymetry of the Colorado River corridor, commonly used canyon-wide locational and thematic data sets, and project-specific geospatial data. New data sets added in FY 2023 include the Lake Powell Digital Elevation Model (DEM) developed by U.S. Geological Survey's Utah Water Science Center (Jones and Root, 2021).

We also developed many derived data sets from the elevation data including water surface elevation polygons representing every 5 feet of elevation change in the reservior, a time series of minimum and maximum lake elevations for each water year, and lake-wide polygon data sets representing the operational tier elevations used by the Bureau of Reclamation to determine water release procedures. All of these data have also been developed as online services and are available in one or more online web mapping applications hosted on ESRI's ArcGIS Online platform.

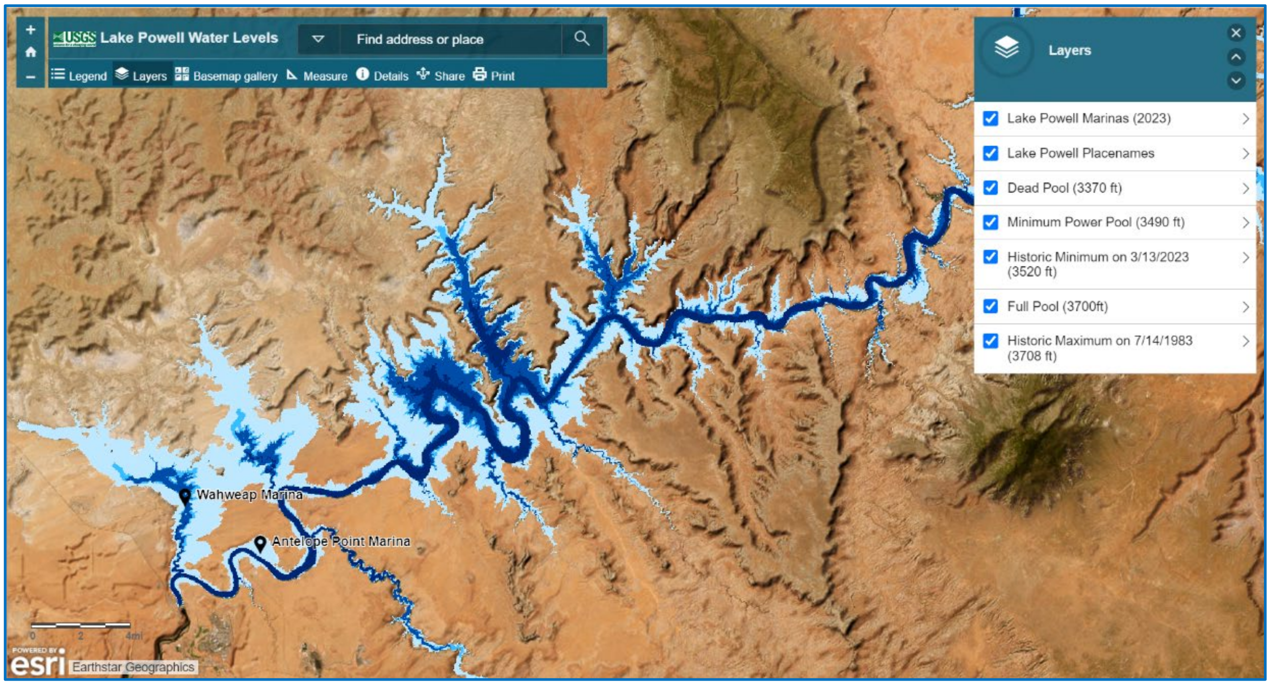

Figure K1. View of new web application that highlights operational tiers of the Lake Powell reservoir at given elevations. Data are derived from Jones and Root, 2021.

Element K.2. Geospatial Data Management, Processing, and Documentation

Geospatial data management tasks included making updates to server hardware and software, updating existing applications to comply with new security measures, and testing and troubleshooting connectivity to internal systems – such as existing relational databases (PostgreSQL, Microsoft SQL Server) – as well as external clients that range from desktop applications (ArcGIS ArcMap and Pro, QGIS) to web-based endpoints (REST services, online applications, ArcGIS Online content, see Project Element K.3. and Products sections). Work performed within this project also includes collaboration, coordination, and occasional oversight of SBSC Information Technology (IT) staff and initiatives as they relate to GCMRC science. This oversight and coordination has benefitted GCMRC by ensuring that proper IT infrastructure and computing resources are made available to GCMRC science staff.

Enterprise Database Management

Project K staff continued to lead the Center in the maintenance and further development of open-source databases, specifically building upon the work in FY 2021 and 2022 to migrate to the PostgreSQL relational database management system (RDBMS). We have expanded the collection of databases now hosted in our Linux-based Postgres environment to eight database endpoints, each uniquely configured to optimize storage and retrieval of either tabular-centric or geospatial-centric data resources for the Center.

One example is GCMRC's Fish Monitoring Database, which has received a great deal of attention for a number of improvements led by Project K. These include better database functionality, workflows employed to import field collected data, and how the data are accessed for reporting and analysis. This effort began with improving the communication between Project K staff and fish biologists who are seen as the data stewards of this information. Through improved coordination efforts, including the hosting of frequent internal meetings and using Microsoft Teams to communicate new processes and workflows, Project K has greatly improved on the entire approach for data entry, quality assurance and quality control (QA/QC) procedures, and reporting out on the status of the fish monitoring database.

In FY 2023, Project K staff initiated and led several fish database workshops to analyze artifacts in the relational database that lacked proper documentation. This process led to developing some normalization criteria in order to improve upon the current database, and to help guide future efforts in redesigning the fish database. Additionally, the team – which includes fish biologist staff and representatives from other agencies – have continued to work toward maintaining clear communication and documenting the status of fish data collection, data entry, and the QA/QC process. We continue to offer access to the Fish Monitoring Database trip status through a widely available data visualization that shows the Month, Trip ID, Total Samples per trip, and Total Specimens per trip. This visualization is shared with all fish cooperators via a dedicated Microsoft Teams channel for fish monitoring. Future plans include making this and similar data visualizations available to the larger GCDAMP community.

Buidling upon the work accomplished in FY 2022, a concerted effort was put forth on making much of the Lake Powell Water Quality database available online through a custom set of data access tools and web-based mapping products. This work involved close coordination with the Lake Powell water quality principal investigator (Deemer) and a significant amount of time to align the host of online data products that will be made available through a custom website in FY 2024.

Staffing challenges

As described in the previous two annual reports (FY 2021 and FY 2022), GCMRC's full-time Database Administrator resigned in September 2021, and Project K has been unable to backfill this position for the entire fiscal years of 2022 and 2023. This position was recently announced in October 2023, with an anticipated hiring occurring within the next month or two. In FY 2021, we added capacity for some database and application development support by transitioning one employee from the Terrestrial Drylands Ecosystems (TDE) branch of SBSC to be a GCMRC employee; however, this employee left for a position with another agency in July 2023, and so this project and GCMRC has once again had to deal with loss of capacity for performing this type of work. While others in the Center have stepped up to be more involved in the data workflow process, hiring the Database Administrator position is still needed in order to more comprehensively manage of the Center's data resources moving forward.

Management of Cloud Environment Usage for Science Project Support

Project K has led the Center in expanding the role of data management to include a hybird-cloud approach for future data needs, and more specific, actively maintains GCMRC's resources in the Amazon Web Services (AWS) cloud environment. This work continues to require coordination at a high-level with GIS and IT staff at the USGS Southwest Biological Science Center (SBSC), USGS CHS team members across the country, USGS project leads from other science centers, and contractual partners from the private sector. There were several goals outlined for this past year, with the most notable as follows:

- Further develop the GCMRC's capacity for working in and building applications in AWS.
- Coordinate with SBSC IT staff to analyze and refine both on-premises data management operations and utilization of cloud storage and computing resources to better support science projects.
- Build more proficiency among science project staff and Project K staff to work relational databases and online data services, and develop new or novel data visualizations that leverage newer technologies and highlights GCMRC science.

Expanding Use of Source Control

Project K has continued to the lead GCMRC in developing and managing geoprocessing scripts, web applications and other work involving programming through online source control and versioning platforms. Leveraging these source control platforms has led to greater efficiency in code development and faster development of new web applications than previously possible. It also has led to greater collaboration between code development for different GCMRC science projects. By continuing to promote and use source control for GCMRC, the Geospatial team can better serve in an advisory role for GCMRC scientists and technical staff and allow for greater collaboration with cooperators and other external entities.

Element K.3. Access to Geospatial Data and Online Data Resources

This Project Element often is the culmination of efforts described in the previous two elements. Without having properly identified data need requirements for other GCMRC science projects and then having those data properly managed, often through the use of enterprise relational database management systems, being able to serve the Center's data resources online becomes more difficult. So, Project Elements K.1 and K.2 are building blocks for improving the access to GCMRC's data resources, including through online applications. Described here are three components of this element: 1) continued maintenance and improvements to GCMRC's online geospatial data, 2) an increase in the use of online data visualizations to support science projects, and 3) the continued emergence of GCMRC's Internet of Things (IoT) data telemetry efforts.

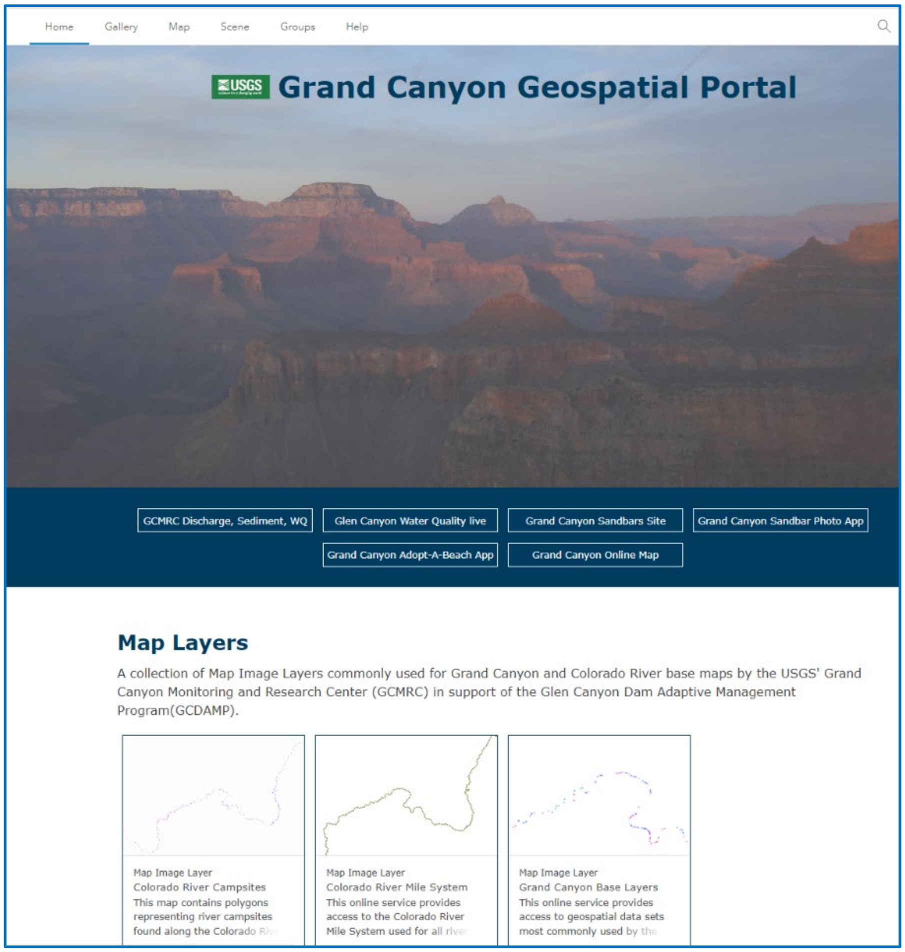

Figure K2. View of Grand Canyon Geospatial portal home page that was redesigned in FY 2023 to provide better access to geospatial data sets and the most-commonly used online data applications.

In FY 2023, the Grand Canyon Geospatial portal was redesigned to provide access on the front landing page to many of GCMRC's data-driven online applications that provide access to valuable data resources. Also, the online geospatial data sets were reorganized into the thematic groups and promoted up to the front landing page, leading to improvement in the ease of locating many of the most commonly used data sets. In addition to these improvements, Project K staff continued to perform all the administration, installation, system upgrades, and content expansion made available through an online portal as well as sharing many of these data services through the ESRI ArcGIS online cloud platform (https://www.arcgis.com/). This work also involved configuring, testing, and publishing new geospatial data sets to the Grand Canyon Geospatial portal that directly support GCMRC science projects. Often administration tasks required close coordination with other USGS IT entities to resolve web-based application and other online content issues, as well as working to improve performance in delivering GCMRC geospatial content online.

Grand Canyon Geospatial portal: https://grandcanyon.usgs.gov/portal/home/

Advances in Data Science Support

Project K has continued to lead GCMRC in the use of Tableau data visualization for developing compelling views of some of the Center's most critical data assets. In the background, Project K continues to manage the licenses for this software in coordination with the USGS' Cloud Hosting Solutions (CHS) team and has expanded on the capacity needed for creating compelling, database-driven analytical capabilities through additional licenses for staff. Additional accomplishments this year included building proficiencies in connecting different data sources in Tableau, filtering data down to appropriate levels, and developing novel techniques for linking cloud-based databases to Tableau Server and publishing those data sources. Much work still remains to expand the use of this software to support other science projects and improve upon ways that managers and stakeholders within the GCDAMP can access scientific data. The online availability of Tableau data visualizations is discussed below.

Internet of Things (IoT) Sensor-to-Cloud Data Transmission

We have expanded the Center's use of the USGS' CHS Sensor Processing Framework and provided unparalleled opportunities for accessing important GCMRC data resources. Perhaps the biggest accomplishment this year was migrating away from the geostationary satellites that the Center has used since approximately 2004 and instituting the first of its kind installation and adoption of Low Earth Orbit (LEO) satellites at the three main gaging and sediment monitoring stations downstream of Glen Canyon Dam (30-mile, 61-mile, and Grand Canyon Gage near Phantom Ranch). This effort marks the first documented use of LEO satellites across the U.S. Geological Survey. The deployments have resulted in nearly continuous uptime of the sediment monitoring sites with greatly increased bandwidth while achieving lower monthly costs for data transmission.

In FY 2023, Project K work focused on improving the stability of the existing IoT study sites. This work involved a considerable amount of re-engineering both physically and in system configurations and programming code used to perform the data telemetry tasks at our established sites. Additionally, this work involved site visits for performing maintenance of our IoT systems; however, with the improvements added over the past year, it is expected that the number of site visits and the amount of system downtime will be greatly reduced. It is important to underline that GCMRC's telemetry sites are not any different than the more traditional field data collection in that these systems have been established and are operating in very remote locations, characterized by extreme conditions and terrain; these characteristics add challenges to perform this type of work.

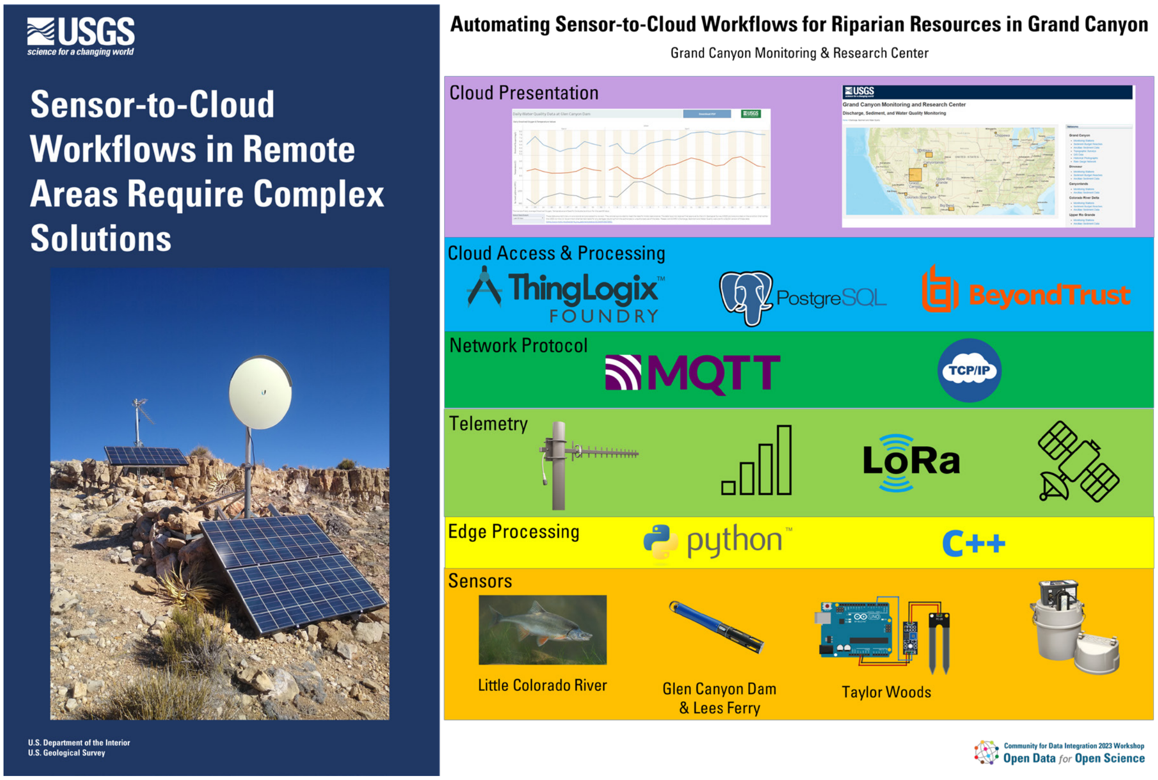

Figure K3. Slide from a presentation given on the advances made in GCMRC's data telemetry using modern Internet of Things technologies. Schematic illustrates the technological stack employed and the workflow used to make the data available online in near real-time.

Continued coordination led by Project K has allowed GCMRC to leverage USGS resources, including continued involvement with CHS and the CHS Sensor Cloud Processing Framework, the Center for Data Integration, and the Actionable and Strategic Integrated Science and Technology (ASIST) project. The list of data telemetry sites include: water quality monitoring at Glen Canyon Dam and the Lees Ferry gaging station, suspended-sediment monitoring at five locations along the Colorado River, and fish antenna array pit-tag data from the Little Colorado River. For the water quality IoT sites, data sent to the AWS cloud via cellular signal are used as the source for displaying certain water quality parameters in near real-time using the Tableau Server software and online data visualization application (Figure K4).

For FY 2023, Project K staff worked to make provisional data available externally to GCDAMP stakeholders and the general public through the data visualization tool. This tool is used by stakeholders, including in formal presentations made by the Bureau of Reclamation and others. The public release process also allowed Project K staff the opportunity to institute some basic filtering of the live, real-time data, thus providing a better online product.

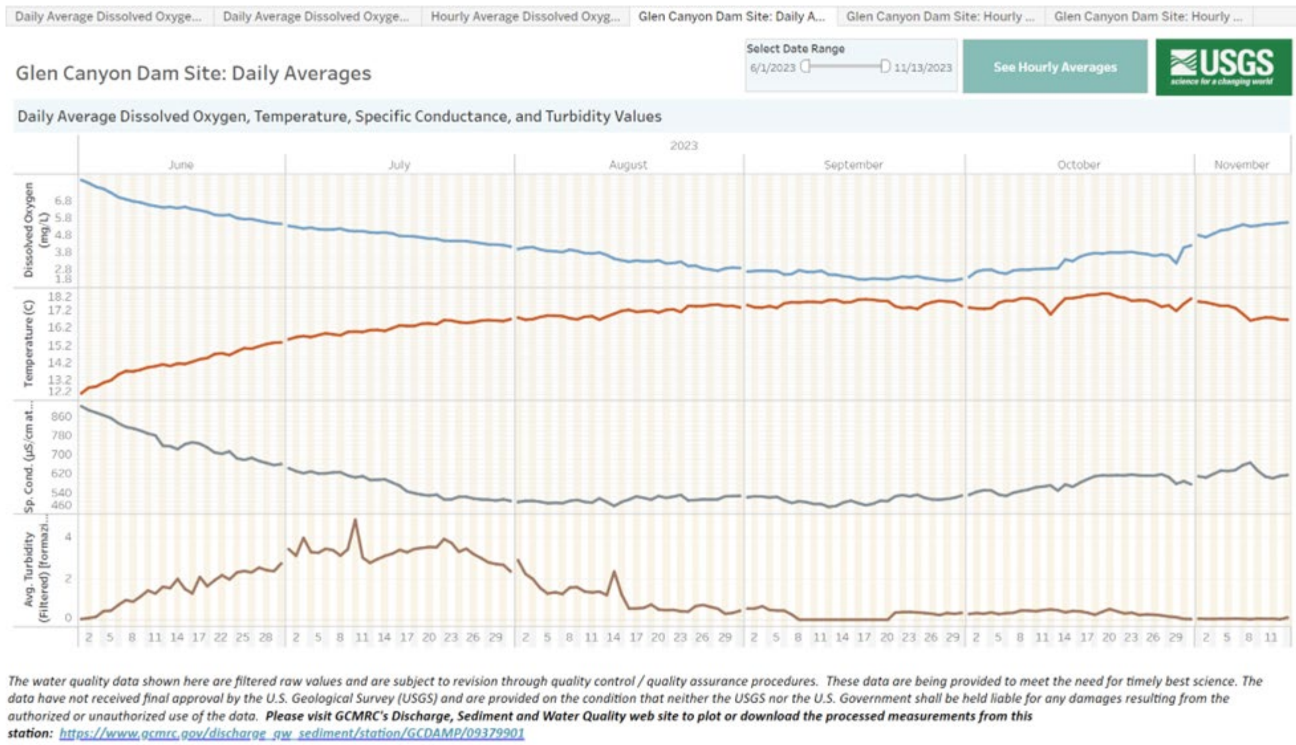

Figure K4. View of online data visualization of Glen Canyon Dam water quality information shared in near real-time, now publicly available with link to quality assessment/quality control version of the data: https://tableau.usgs.gov/views/colorado-river-water-quality-gcd/GlenCanyonDamSiteDailyAverages.

By leveraging the power of cloud computing, we are able to view and share these important data almost instantaneously, improving on a process that would take days to weeks to do previously. Now, GCMRC researchers and other DOI entities are able to view these data through a series of dashboard tools, share the data visualizations with other researchers and stakeholders, and download the data.

References

ESRI, 2020, ArcGIS Enterprise software—copyright 1995–2020: Redlands, Calif., Environmental Systems Research Institute, accessed May 14, 2020, https://www.esri.com/en-us/legal/copyright-trademarks/.

Jones, D.K., and Root, J.C., 2021, Modified topobathymetric elevation data for Lake Powell: U.S. Geological Survey data release, https://doi.org/10.5066/P9H60YCF.

Project K Budget

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$392,014	$3,500	$3,700	$0	$0	$50,393	**$449,607**
Actual Spent	$299,091	$5,862	$16,404	$0	$0	$40,565	**$361,921**
(Over)/Under Budget	**$92,923**	**($2,362)**	**($12,704)**	**$0**	**$0**	**$9,828**	**$87,686**

COMMENTS
FY23 Comments: - Unspent Salaries is due to staff turnover and HR-delays in hiring of a Database Administrator and a Geographer. - Overspent Travel & Training is due to rescheduled meetings and conferences post Covid-19. -Overspent funds in Operating Expenses is for purchases of necessary information technology hardware and equipment for remote data collection and transmission.

Project K Deliverables: Geospatial Science and Technology

Presentations:

Gushue, T.M., Thomas, J.E., Andrews, C.M., 2023, Modernizing data telemetry efforts for important riparian resources in Grand Canyon—poster presentation: Glen Canyon Adaptive Management Program, Technical Work Group Annual Reporting Meeting, Phoenix, Ariz., January 22, 2023.

Thomas, J.E., and Gushue, T.M., 2023, Automating sensor-to-cloud workflows for riparian resources in Grand Canyon—poster presentation: U.S. Geological Survey, Community for Data Integration (CDI) Workshop, National Conservation Training Center, Shepherdstown, W.Va., May 5, 2023.

Science Communication Products:

Gushue, T.M., Thomas, J.E., Andrews, C.M., 2023, Advancing data telemetry capabilities using long range wide area network telemetry and the cloud sensor processing framework: Science Spotlight article published in the U.S. Geological Survey, Director's "Need to Know" blogpost, October 16, 2023.

Gushue, T.M., Thomas, J.E., Griffiths, R., 2023, SBSC's Grand Canyon Monitoring and Research Center Adds Low Earth Orbit (LEO) Satellite Dish to Historic Grand Canyon Sediment Gaging Station: U.S. Geological Survey online news article, April 14, 2023, https://www.usgs.gov/centers/southwest-biological-science-center/news/sbscs-grand-canyon-monitoring-and-research-center.

Code Development Products Maintained in Source Control (GitLab):

Byerley, E.B., 2023, Geospatial tools, *in* SBSC-GCMRC-GIS-Geospatial Tools Repository: https://code.usgs.gov/sbsc/gcmrc/gis/geospatial-tools

Byerley, E.B., 2023, Lake Powell visualization tools, *in* SBSC-GCMRC-GIS-Lake Powell Geospatial-Lake Powell Elevations + Extents Repository: https://code.usgs.gov/sbsc/gcmrc/gis/lake-powell-geospatial/lakepowell-elevations-extents

Thomas, J.E., 2023, Foundry PostgreSQL download tool, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/Foundry_PostgreSQL_Download_Tool?ref_type=headsab

Thomas, J.E., 2023, Grand Canyon machine learning camera, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/grand-canyon-machine-learning-camera

Thomas, J.E., 2023, NWIS data retrieval, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/NWIS_Data_Retrieval?ref_type=heads

Thomas, J.E., 2023, Short burst telemetry toolkit, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/Short%20Burst%20Satellite%20Telemetry%20Toolkit?ref_type=heads

Thomas, J.E., 2023, Water quality IoT, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/water-quality-iot-code

Online Content Maintained by Project:

Online Data Visualizations

Gushue, T.M, and Thomas, J.E., 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Daily water quality data at Glen Canyon Dam—online data visualization, last modified September 8, 2023, https://tableau.usgs.gov/views/colorado-river-water-quality-gcd/GlenCanyonDamSiteDailyAverages

Hensleigh, J., Andrews, C.M., Voichick, N., and Deemer, B., 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Lake Powell vertical water quality profiles—online data visualization, last modified December 18, 2022, https://tableau.usgs.gov/views/view-profiles-by-station-collection-date/ProfileByStationVisitDateDashboard

List of Websites and Web Applications

- Adopt-A-Beach Sites Photo Viewer: https://grandcanyon.usgs.gov/gisapps/adopt-a-beach/index.html
- Geospatial Services page (for advanced GIS users and developers): https://grandcanyon.usgs.gov/gisapps/restservices/index_wret.html
- Grand Canyon Geospatial Portal: https://grandcanyon.usgs.gov/portal/home/index.html
- Sandbar Monitoring Photo Viewer: https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html

- Updated Sandbar Monitoring Data website: https://www.usgs.gov/apps/sandbar/

Web Content on ESRI ArcGIS Online

- Access to Geospatial Data Holdings – ESRI's ArcGIS Online (Note: some content not shared to the public): http://usgs.maps.arcgis.com/home/search.html?q=GCMRC&t=content
- Predicted Shorelines for High Flows on the Colorado River Application: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=721001c63d91458883340f05c68c55f4
- River Campsite Web Application: https://usgs.maps.arcgis.com/home/item.html?id=0f9f6575bfee406cac6593b293883665

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

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC Thomas Gushue, USGS, GCMRC Keith Kohl, USGS, GCMRC
Email	jsankey@usgs.gov		
Telephone	(928) 556-7289		

Goals and Objectives

This project seeks to acquire high-resolution multispectral imagery, a digital elevation model (DEM), and a Digital Surface Model (DSM) of the Colorado River and riparian area from the forebay of Glen Canyon Dam downstream to Lake Mead, and along the major tributaries to the Colorado River. The data collection mission occurred in 2021. During 2022 the data were iteratively reviewed and pre-processed by the contractor and GCMRC, and during 2023 the data were processed by GCMRC and are pending publication by USGS.

The data sets derived from remote sensing overflights have proven to be extremely valuable to all the research projects conducted by GCMRC over the past two decades. Importantly, scientific research, which relied heavily on these data, was the basis for the 2016 LTEMP (U.S. Department of the Interior, 2016a). Given that the last overflight was conducted in 2013, and given the physical, geographic and logistical constraints of the Colorado River in Grand Canyon, system-wide remotely sensed data were deemed necessary in 2021 to complement ground-based data collection and assist with the GCMRC's efforts to effectively assess these impacts for the entire river ecosystem over decadal time frames. The imagery and derivative data products from overflight remote sensing are used either directly or indirectly by every science project reporting herein to address every resource goal of the LTEMP.

While this work is discussed within the context of FY 2023 of the FY 2021-2023 Triennial Work Plan (TWP), the nature and justifications for conducting the overflight are directed at the GCMRC's ability to respond to and deliver information for the LTEMP implementation process that tracks decadal-scale changes to resources system-wide. As such, the overflight is a scientific effort that has both an immediate and a longer-term payoff; future LTEMP studies will require similar information that can be effectively derived from remotely sensed data acquired over the coming decades. For these reasons, this project is mission-critical to successfully inform the GCDAMP on the performance of the LTEMP ROD (U.S. Department of the Interior, 2016b).

Project Elements

Element L.1.

Science Questions/Hypotheses Addressed

Science Question 1

- How has landcover changed in the Colorado River Ecosystem (CRe) in 2021 relative to preceding decades?

Science Question 2

- How are observed landcover changes related to dam operations, other land use, and management activities, as well as climate and other environmental factors in the ecosystem?

Results

To address the defined Science Questions for Project L the FY 2023 focus was to (Table L1): 1) implement quality assurance/quality control (QA/QC) and final modifications to the data sets acquired by the contractor Fugro Geospatial, Inc. (Fugro), during the 2021 overflight, 2) publish, through the USGS data release publication process, the finalized data sets of the high-resolution multispectral image orthomosaic and a digital surface model for the Colorado River riparian ecosystem from Glen Canyon Dam to Lake Mead, and 3) begin working on derivative data products, including water, sand, and vegetation maps.

In FY 2022, Fugro delivered the final revised data sets and GCMRC accepted the data sets and closed the contract with Fugro for the 2021 overflight data acquisition and delivery. The contractor was responsible for initial data processing, including mosaicking of a DSM (digital surface model) and interpolation to develop a DEM (digital elevation model), as well as creating orthorectified images of the individual flightlines to build a complete image orthomosaic for the collection area. The processes of developing the image mosaic, and of developing a DEM from the DSM were new contractor deliverables for the 2021 image collection; in 2009 and 2013, for example, GCMRC scientists were responsible for creating this data product. Including the mosaic and DEM as deliverables in the contract was intended to reduce project costs and make it possible for GCMRC scientists to work on derivative data products and related science more quickly after the overflight than from previous missions.

Data Sets Delivered by Contractor

- DEM (digital elevation model) and DSM (digital surface model); 1-meter pixel resolution.
- L2 (orthos): individual flightlines collected from the airborne sensor. This includes all Nadir look lines as well as supplemental Backward and Forward look strips to compensate for “Hot-Spots” and “Glint” present in Nadir channels.

- Orthomosaic: Complete mosaic using error free flightlines; 20cm pixel resolution with four bands (blue, green, red, near-infrared) (Figure L1). These data are organized into 105 image files based on USGS 7.5 quadrangle maps (Figure L2).

In FY 2023, GCMRC project staff conducted image processing steps to fix issues associated with shadowing and topographic distortion in discrete locations throughout the data sets and prepared them for publication as USGS data sets. Project staff used flightlines from the L2 (orthos) deliverable to modify the mosaic and remove errors as necessary to prepare the data for publication. We also withheld ground control locations and completed an internal accuracy assessment of the registration of the image data and the vertical accuracy of the DSM and DEM data sets (Table L2). The horizontal accuracy of the image orthomosaic product is reported as a Root Mean Square Error (RMSE) of 0.297 meters.

The mosaic was compared to the 2013 mosaic data set to make sure that the data are acceptable to evaluating decadal trends in the Colorado River ecosystem. It was found that the data occupy a higher region of the 16-bit range (from 0-65535) and also have a greater spread through this range, which we expect to allow for more precise image classification into various landcover types than in previous data sets (Figure L3).

At the time of writing this report, the image mosaic data set, DSM, and DEM data are pending publication as USGS data releases, and those data are expected to be published in Q1 of FY 2024. Now that those data sets are pending publication and the reviews and revisions for quality assurance, quality control (QA/QC) and accuracy are completed, GCRMC scientists have begun working on derivative data products. The planned derivative products include water, sand, and vegetation maps. GCMRC scientists are currently working on the water map, which shows all water in the Colorado River channel in the imagery which was acquired during a low steady-flow release from Glen Canyon Dam of approximately 8,000 cubic feet per second (cfs; Figure L4). The water map also shows water within tributaries in the imagery (Figure L4).

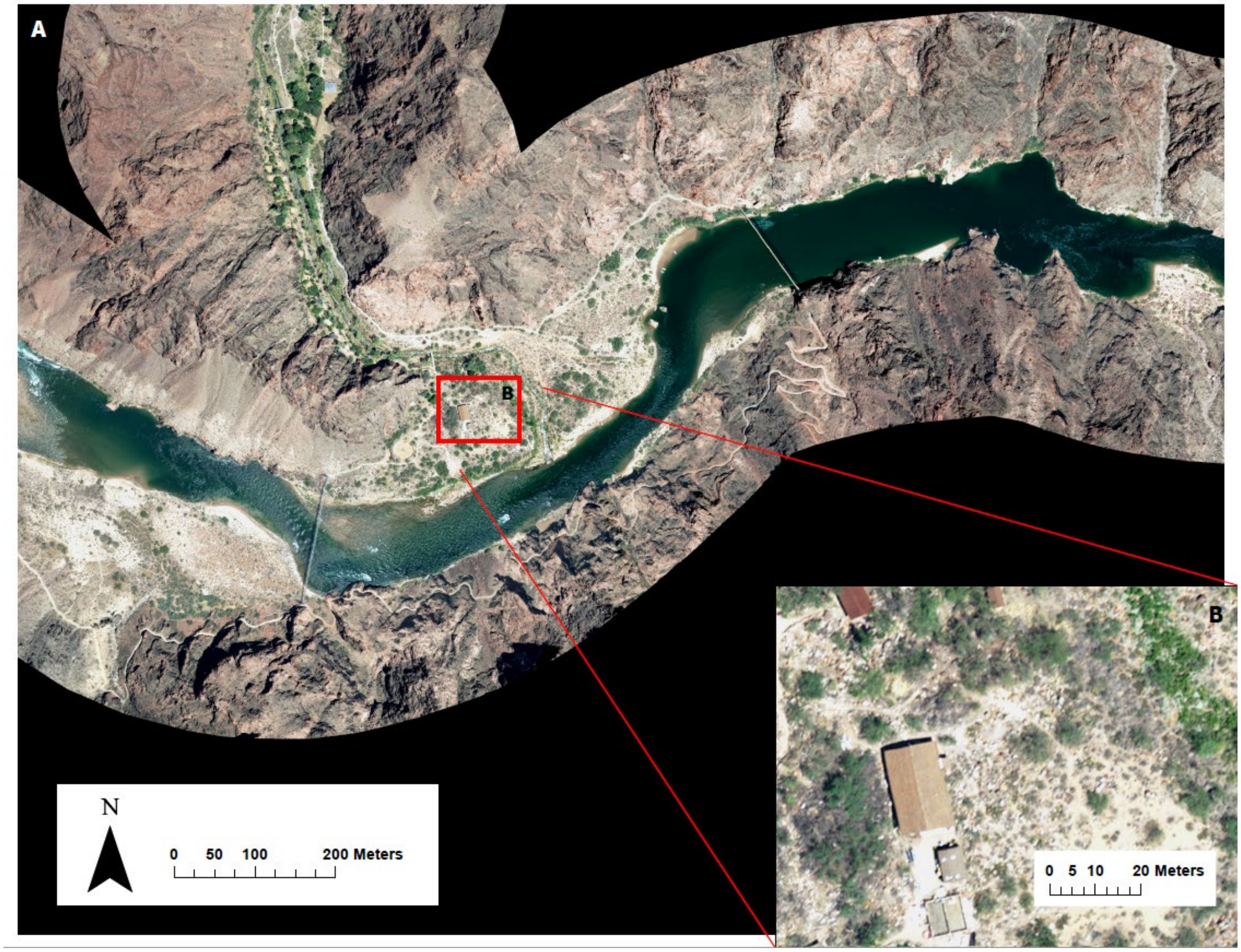

Figure L1. Final version of the orthomosaic data product derived from the overflight aerial imagery acquired in 2021 in the vicinity of Phantom Ranch in Grand Canyon National Park (A) with a zoomed view (B) depicting structures and vegetation at high resolution.

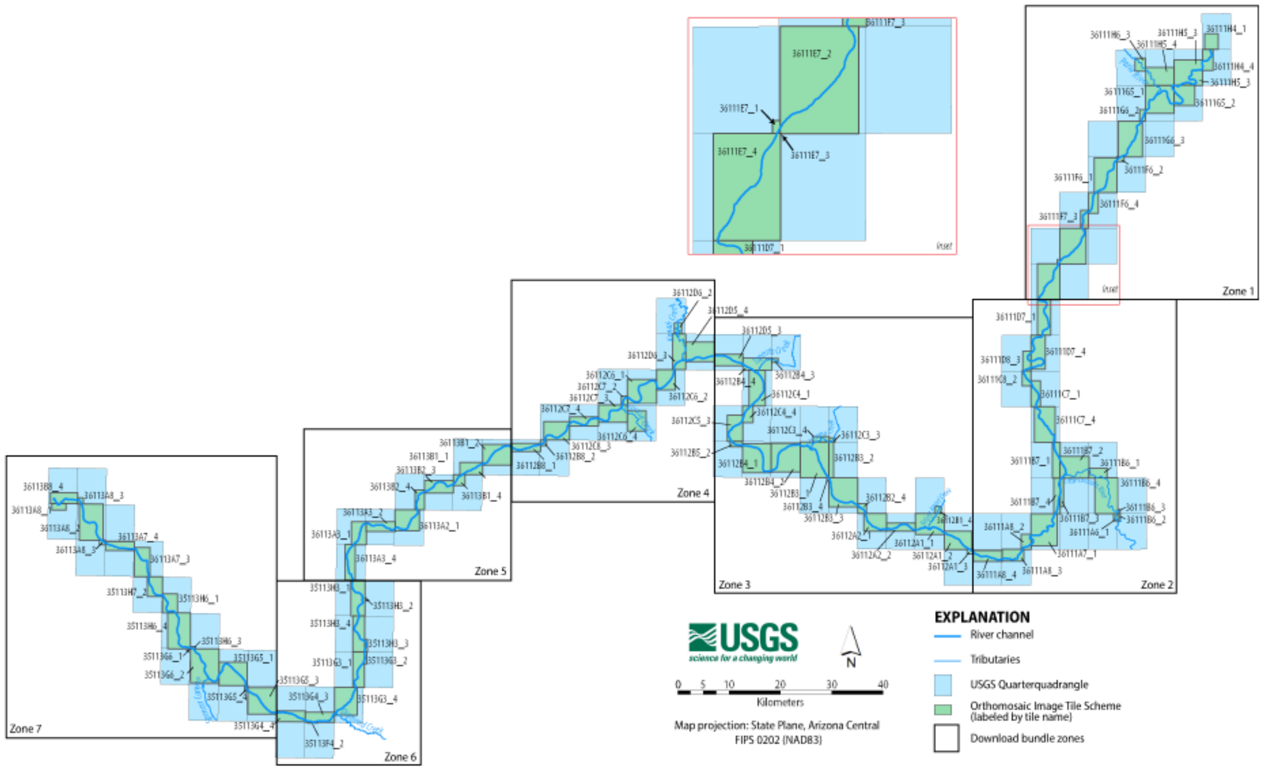

Figure L2. U.S. Geological Survey Grand Canyon Monitoring and Research Center index map showing the map tile scheme used to subset the orthomosaic imagery overlain on the USGS quarter-quadrangles (QQ). The orthomosaic imagery is subset into 105 files following the tiling scheme depicted here, and then further organized by the 7 zones shown here. The map tile scheme used to subset the orthomosaic was modified from the standard USGS quarter-quadrangle (QQ) and quarter-quarter-quadrangle (QQQ) map borders, to best fit the river corridor. The 105 tiles are labeled (and associated data files are named) using QQQ names. However, please note that tile boundaries do not strictly adhere to the QQQ or QQ boundary associated with their name. Each of seven download bundle zones shown here can be accessed as a compressed zip file.

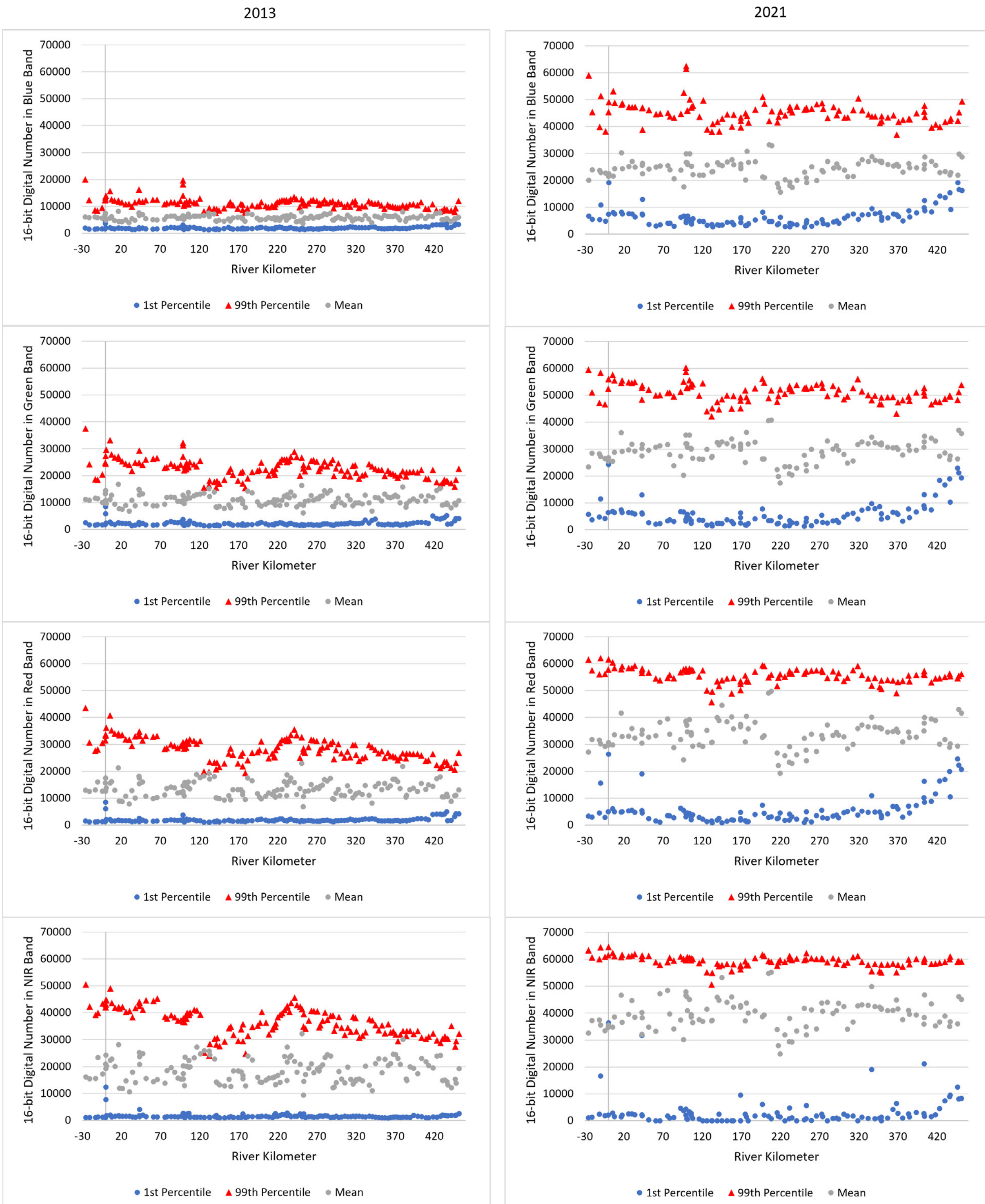

Figure L3. Distribution of digital number (DN) values for each image tile along the river corridor. River distance is referenced as either upstream (-) or downstream (+) from Lees Ferry (0 km; vertical line). Plots include values from the 2013 image in the first column and from 2021 in the second column.

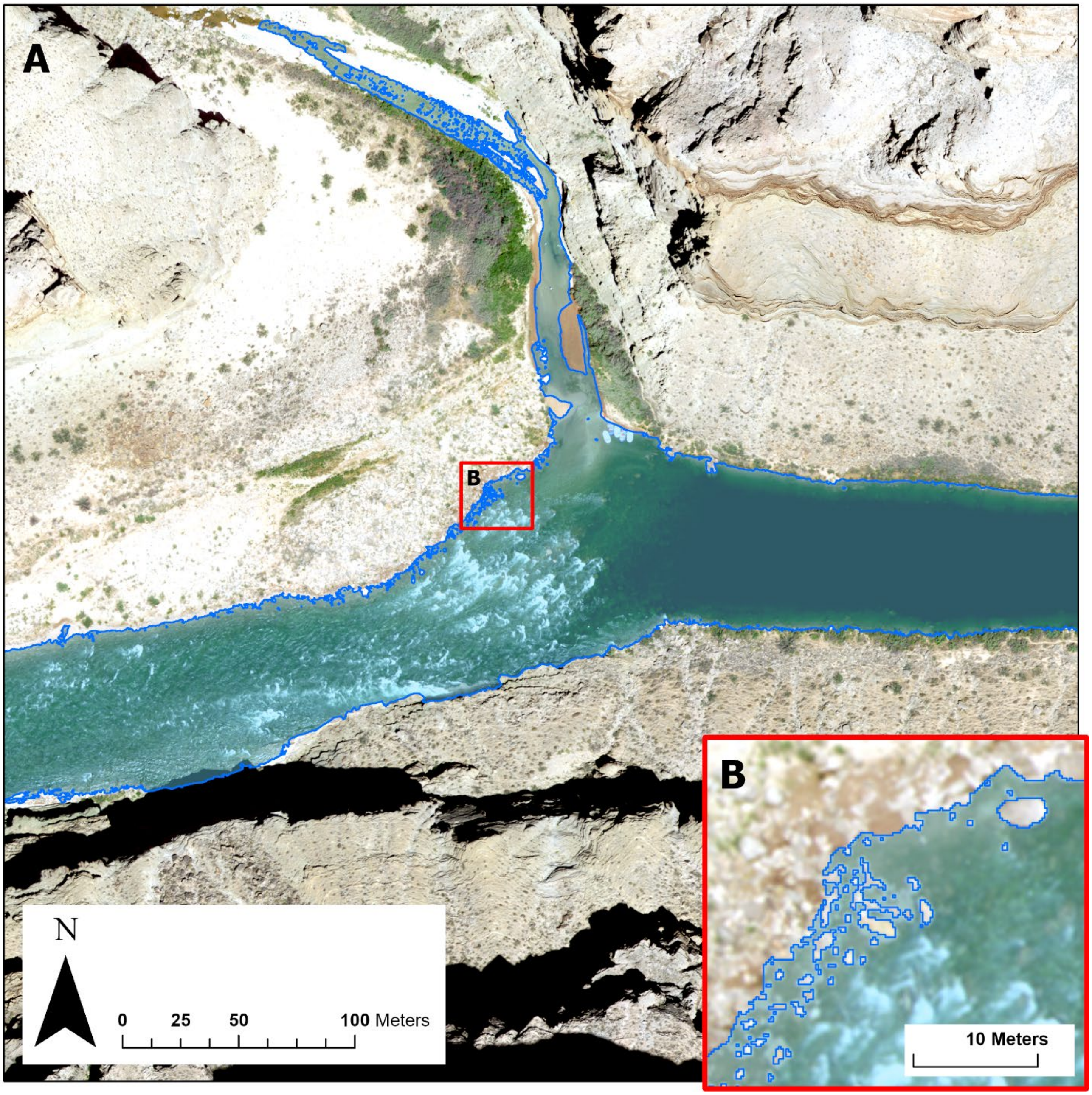

Figure L4. Water classification at the confluence of Kanab Creek with the Colorado River in Grand Canyon National Park (A) with a zoomed view (B) highlighting precision of the classification along complex shorelines at high resolution.

Table L2. Timeline of major activities and work effort for the overflight mission and remote sensing data analysis in Project L during the FY 2021-23 Triennial Work Plan.

<table>
<tr><th>Fiscal Year</th><th>Quarter(s)</th><th>Activities</th></tr>
<tr><td rowspan="4">2021</td><td>1st</td><td>Write Task Order and negotiate contract with GPSC (USGS Geospatial Products and Services Contracts) and contractor for overflight mission consisting of imagery and digital topographic data acquisition</td></tr>
<tr><td>2nd</td><td>Contract awarded to Fugro Geospatial Earth Data
Coordinate logistics for the overflight mission with GCDAMP agencies and stakeholders.
Plan GCMRC logistics, including the rim- and river-level operations to be conducted by GCMRC in coordination with the contractor.</td></tr>
<tr><td>3rd</td><td>Overflight mission
Rim-level GPS base station operations
River-level accuracy assessment and ground-truthing operations.</td></tr>
<tr><td>4th</td><td>Monitor image processing performed by Fugro (contractor)</td></tr>
<tr><td rowspan="3">2022</td><td>1st</td><td>Data delivered to GCMRC
QA/QC performed by GCMRC in coordination with vendor</td></tr>
<tr><td>2nd</td><td>Final modifications to mosaic performed by GCMRC</td></tr>
<tr><td>3rd & 4th</td><td>Begin publication process at GCMRC for finalized mosaic</td></tr>
<tr><td>2023</td><td>All</td><td>Image mosaic published by GCMRC
Landcover classification maps produced by GCMRC remote sensing staff</td></tr>
</table>

Table L2. Comparison of 2021 mosaic with GCMRC survey-control network (n=47 independent ground control points not provided to, or used by, the contractor Fugro in the aerotriangulation to orthorectify and georeference the imagery). All values in meters.

Horizontal accuracy assessment statistic	Easting (X)	Northing (Y)	Combined (XY)
Sum of square errors (SSE)	2.032	2.117	4.149
Mean square error (MSE)	0.043	0.045	0.088
Root mean square error (RMSE)	0.208	0.212	0.297
Accuracy at 95% confidence	0.408	0.416	0.514

References

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

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

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

Project L Budget

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$181,637	$0	$0	$80,596	$0	$25,346	**$287,579**
Actual Spent	$80,251	$0	$0	$99,269	$79,935	$13,108	**$272,563**
(Over)/Under Budget	**$101,386**	**$0**	**$0**	**($18,673)**	**($79,935)**	**$12,238**	**$15,016**

COMMENTS
FY23 Comments: -Underspent Salaries is due to staff turnover in the previous year and change in mechanism for completing work. -Overspent Cooperative agreements is due to change in mechanism to complete work from GCMRC staff to cooperator. -Overspent To Other USGS Centers is due to the change in mechanism to complete work from GCMRC to other USGS center staff.

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

Presentations:

Sankey, J.B., Bransky, N., Durning, L., Gushue, T., Kohl, K., and Pigue, L.M., 2023, Overflight remote sensing in support of long-term monitoring and LTEMP—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, January 24-25, 2023, Phoenix, Ariz, https://www.usbr.gov/uc/progact/amp/twg.html.

Sankey, J.B., and Sankey, T., 2022, Measuring surface topography and vegetation changes in complex terrain with lidar and photogrammetry—presentation abstract: American Geophysical Union Fall Meeting, Chicago, Ill., v. 2022, p. GC15F-05, December 12-16, 2022.

Sankey, J.B., Sankey, T.T., Caster, J., and Debenedetto, G., 2023, Surface topography and vegetation changes from UAV and ground-based lidar data fusion—presentation abstract: IALE-North America 2023, Riverside, Calif., March 19-23, 2023.

USGS Data Releases:

Alfermann, A., Sankey, T.T., Bransky, N., and Sankey, J., *In Prep*., Vegetation and water classifications in 2009, 2013, and 2021 for a segment of the Paria River upstream of the Colorado River confluence, Arizona, USA: U.S. Geological Survey data release.

Sankey, J.B., Bransky, N., Pigue, L., and Kohl, K., *In Prep*., Four band image mosaic of the Colorado River corridor downstream of Glen Canyon Dam in Arizona derived from the May 2021 Airborne image acquisition: U.S. Geological Survey data release, to be published at https://doi.org/10.5066/P9BBGN6G.

Sankey, J.B., Kohl, K., Gushue, T., Bransky, N., Bedford, A., Durning, L., and Davis, P.A., *In Prep.,* DSMs for Colorado River Corridor in Grand Canyon National Park and Glen Canyon National Recreation Area—2002, 2009, 2013 and 2021 and DEM for 2021: U.S. Geological Survey data release.

Project M: Leadership, Management, and Support

Project Lead	Andrew Schultz, GCMRC Chief	**Principal Investigator(s)** (PI)	Andrew Schultz, GCMRC Chief Mark Anderson, GCMRC Deputy Chief
Email	aschultz@usgs.gov		
Telephone	916-601-1439		

Goals and Objectives

During FY 2023, the budget for Project M included funding for leadership personnel including salaries, travel, and training for the Chief and Deputy Chief. The budget also included part of the salaries for a technical information specialist and a budget analyst. The vehicle section of the budget covers the costs associated with U.S. Department of the Interior (DOI) owned and GSA leased vehicles that USGS Grand Canyon Monitoring and Research Center (GCMRC) uses for travel and fieldwork. Costs include fuel, maintenance, and repairs for DOI owned vehicles and monthly lease fees, mileage costs, and repair costs for accidents and damages for GSA leased vehicles. This project also includes the costs of Information Technology (IT) equipment for GCMRC. Salaries, travel, and training for all logistics staff are also included in this project's budget.

In addition, funding from Project M helped support the Partners in Science program with Grand Canyon Youth, a nonprofit organization that provides youth (ages 10-19) with educational experiences along the rivers and canyons of the Southwest, including the Grand Canyon. Scientists from GCMRC, National Park Service, Western Area Power Administration, and the Spring Stewardship Institute participated in the three Partners in Science river trips conducted in FY 2023 during which they helped train the next generation in the scientific process, described the importance of science to DOI's adaptive management efforts on the Colorado River, and trained them in data collection efforts in support of the FY 2021-23 Triennial Work Plan. Data were collected in support of understanding nutrient dynamics (Project E), aquatic algae, invertebrate populations, and bat activity (Project F).

Project M Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$681,808	$20,000	$168,208	$0	$0	$109,822	**$979,838**
Actual Spent	$502,889	$16,462	$353,722	$0	$0	$110,208	**$983,281**
(Over)/Under Budget	**$178,919**	**$3,538**	**($185,514)**	**$0**	**$0**	**($386)**	**($3,443)**

COMMENTS

FY23 Comments:
- Underspent Salaries is due to staff turnover, and USGS providing some funding for GCMRC leadership salaries.
- Underspent Travel & Training was due to meetings and conference cancellations.
- Overspent funds in Operating Expenses is due to hiring incentives, Information Technology, and rising costs for vehicle maintenance and fuel.

Logistics Budget

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$273,839	$3,000	$848,520	$11,000	$0	$142,384	**$1,278,743**
Actual Spent	$294,311	$168	$874,601	$48,350	$0	$149,023	**$1,366,453**
(Over)/Under Budget	**($20,472)**	**$2,832**	**($26,081)**	**($37,350)**	**$0**	**($6,639)**	**($87,710)**

COMMENTS

FY23 Comments:
- Overspent Salaries is due to higher employee salaries and overtime.
- Underspent funds for Travel & Training were due limited training and meetings attendance.
- Overspent funds in Operating Expenses is due to rising costs of fuel and food.
- Overspent funds in Cooperative Agreements is due to the Grand Canyon Youth cooperative agreement adding an annual trip for tribal youth.

Project N: Hydropower Monitoring and Research

Project Lead	Lucas Bair	**Funded Principal Investigator(s)** (PI)	Lucas Bair, USGS, GCMRC
Email	lbair@usgs.gov		
Telephone	928-556-7362		

Goals and Objectives

The overall objective of Project N is to identify, coordinate, and collaborate with external partners on monitoring and research opportunities associated with operational experiments at Glen Canyon Dam designed to meet hydropower and energy resource objectives, as stated in the LTEMP Environmental Impact Statement (EIS) and its Record of Decision (ROD; U.S. Department of the Interior, 2016a), and the Guidance Memo.

Operational experiments include proposed experiments in the LTEMP EIS (U.S. Department of the Interior, 2016b), and other identified operational scenarios at Glen Canyon Dam to improve hydropower and energy resources, while consistent with improvement and long-term sustainability of other downstream resources. In FY 2023 Project N prioritized the development of an optimization tool to better consider impacts of other proposed experiments on hydropower and energy as part of the experimental design.

Science Questions Addressed & Results

In FY 2023, Lucas Bair collaborated with researchers from the University of California at Davis, Utah State University, and researchers within the USGS Grand Canyon Monitoring and Research Center to further develop a constrained optimization computer model that schedules production of hydropower at Glen Canyon Dam (GCD). Updates in model development in FY 2023 included advances in speed and solver performance and the overall structure of the model to incorporate many different hydrological and electricity price sector scenarios.

The hydropower optimization model closely follows Harpman (1999), where the hydropower operator's objective is to identify the load following path that maximizes the economic value (minimizes costs) in the electricity sector. This model allows researchers to estimate the costs of experimental flows at GCD when managing downstream physical and biological recourses, including scenarios with different future power system scenarios. This model is being integrated with biological and physical models as part of Project J.1.

To run this model stand-alone, we assume that hydropower generated from GCD constitutes only a small portion of the electricity in the Southwest region (its sole market); thus, the operator is a price-taker and considers prices to be exogenous and known (U.S Department of the Interior, 2016).

Similarly, the hourly flow through GCD is assumed to have negligible impact on reservoir elevation within a month. The economic cost of all near-term experimental flows are short-run costs. In other words, power system capacity replacement costs are not incurred because no reallocation of water release volumes occurs in August, when capacity is assessed (Interior, 2016b).

Hydropower production (MW) generated at the GCD energy is a function of flow through the turbines and reservoir elevation, both of which are assumed to be constant over an hour time step. Hydropower production is subject to several operational constraints, such as the amount of water available for release, maximum and minimum flow constraints, and ramp constraints (see U.S. Department of the Interior, 2016b for a full list of the operational constraints).

Here we provide an example of the hydrograph that the hydropower optimization model generates over a representative week in April. The optimal dispatch is based on representative load following release volumes from GCD over the past three years. The baseline prices used to estimate revenue from optimal dispatch are based on historical locational marginal price from the California Independent System Operator Open Access Same-time Information System (http://oasis.caiso.com/mrioasis/logon.do). These results from the hydropower optimization models (Figure N1) are consistent with past analysis (U.S. Department of the Interior, 2016b) and can be used to identify the optimal (minimum costs) implementation of experiential flows that are consistent with achieving downstream physical and biological resource goals.

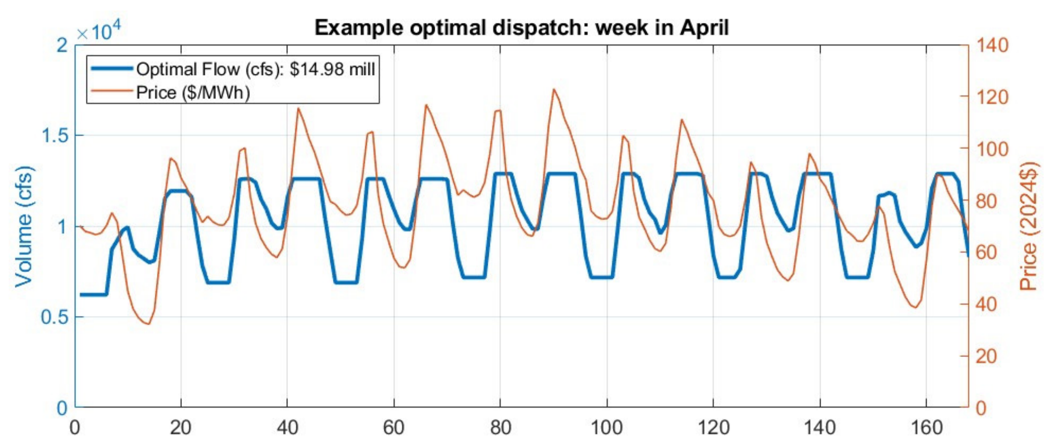

Figure N1. Optimal dispatch for hydropower production. The x-axis shows flow hours. Provisional data, subject to change.

This short-run hydropower optimization allows for an estimation of economic costs of experimental flows and integration of hydropower costs with predictive models of other resources (Project J.1). This integration is important in the assessment of cost-effective approaches to meet downstream resource goals and will assist in the prioritization of monitoring and research related to downstream resource goals.

For a detailed description of power system modeling of hydropower in the Colorado River Basin, see U.S. Department of the Interior, Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement, Appendix K: Hydropower systems technical information and analysis (U.S. Department of the Interior, 2016b).

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Project N Budget

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$16,504	$1,500	$2,500	$0	$0	$2,588	**$23,092**
Actual Spent	$19,684	$0	$0	$0	$0	$2,485	**$22,169**
(Over)/Under Budget	**($3,180)**	**$1,500**	**$2,500**	**$0**	**$0**	**$103**	**$923**

COMMENTS
FY23 Comments: -Overspending Salaries is due to higher employee salary and benfits costs. -Underspent Travel & Training is due to planned travel through project J. -Underspent funds in Operating Expenses was for software that was provided by USGS licensing at no cost to the project.

Project N Deliverables: Hydropower Monitoring and Research

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., and Bair. L.S., *In Prep.,* The economic cost of designer flows in river conservation.

Project O: Is Timing Really Everything? Evaluating Resource Response to Spring Disturbance Flows

Project Lead	Theodore Kennedy	Principal Investigator(s) (PI)	Theodore Kennedy, USGS, GCMRC Paul Grams, USGS, GCMRC Lucas Bair, USGS, GCMRC
Email	tkennedy@usgs.gov		
Telephone	(928) 556-7374		

Goals and Objectives

Disturbance is a critical natural process for many physical and biological resources in streams and rivers. High-Flow Experiments (HFEs) are the principal type of flood disturbance described in the LTEMP Environmental Impact Statement (EIS) (U.S. Department of the Interior, 2016a) and the only approved tool for rebuilding sandbar habitats that are eroded by dam operations and for diminished sediment supply.

For many resources, spring-timed HFEs would be ideal: the pre-dam hydrograph had snowmelt-driven spring peaks; native fishes, insects, and plants have life cycles that are adapted to spring high flows; the main recreational boating season that drives the use of sandbars for camping occurs in spring-summer; and strong winds that drive aeolian sand transport processes to preserve archaeological sites occur in spring. Yet HFEs most often occur in the fall because the HFE protocol in the LTEMP has narrowly defined implementation windows that do not allow an HFE to be triggered in the spring based on sediment inputs from the preceding year.

The objective of Project O is to identify whether a Spring Disturbance Flow within the constraints of the LTEMP Record of Decision (ROD) (U.S. Department of the Interior, 2016b) is a useful tool for enhancing LTEMP resource goals.

Project Elements

Element O.1. Does Disturbance Timing Affect Food Base Response?

Matrix Population Models

Aquatic invertebrates provide a critical link between ecosystem productivity (algal production from nutrients and light) and higher trophic levels (fishes, birds, bats, and other consumers) (Baruch and others, 2021). Changing reservoir elevations and operations are a strong lever governing river and riparian food webs via effects on invertebrate populations and diversity.

Invertebrate population models needed to explore this connection are being developed by collaborators at Oregon State University and will be implemented to test the effects of the 2021 spring disturbance flow on invertebrate taxa that are common in Lees Ferry (e.g., *Gammarus lacustris*, New Zealand mudsnail (*Potamopyrgus antipodarum*), midges (Chironomidae), and blackflies (Simulium spp.)) and also species that are not presently found in Lees Ferry but are common in other tailwaters (e.g., mayflies in the genus *Baetis*). We will use these models to forecast the effects of the spring disturbance flow on components of the invertebrate food base critical to native fishes and other consumers.

Population models developed by Oregon State University directly connect streamflow dynamics to population responses of organisms (Lytle and others, 2017; McMullen and others, 2017; These models incorporate flow variability including low flows, high flows, and load-following fluctuations, seasonal temperature changes, and changes in primary productivity to forecast population sizes for a wide diversity of aquatic invertebrates. The core structure is a stochastic, density-dependent, stage-based matrix population model iterated at biweekly timesteps. Flow variability is incorporated via direct mortality effects (from low flow or flood events) as well as changes to ecosystem productivity due to different flows.

Temperature regulates the fundamental tradeoff between growth and development, which ultimately determines the timing and abundance of availability of invertebrates for fish and other consumers. We have parameterized the model with vital rates for individual species (mortality rates, fecundity, growth rates) from published values in the literature, from long-term drift data collected by USGS at Lees Ferry, and from benthic data collected during HFEs and the 2021 spring disturbance flow event. Thus, the model uses inputs of biweekly streamflow and river temperature data to forecast population sizes of aquatic invertebrates of interest. Preliminary results demonstrate that the timing of flow disturbances (i.e., HFEs) affect invertebrate population response (see Figure O1). Invertebrate abundance is a strong lever on growth and productivity of rainbow trout and native species that are found downstream in Grand Canyon including humpback chub (*Gila cypha*); see Kennedy and others, 2013. Additional updates on these modeling efforts will be presented at the Glen Canyon Dam Adaptive Management Program (GCDAMP) Annual Reporting Meeting in January 2024.

Water-Quality Monitoring at Lees Ferry

In FY 2023, Project O funds were used to purchase a new water quality buoy that will allow accurate measurements of dissolved oxygen and other parameters across all flow levels. Existing water quality monitors deployed from the Lees Ferry gage house are unable to provide accurate measurements of dissolved oxygen, in particular, owing to stagnant flow in the vicinity of the gage house when discharge is less than ~10,000 ft^3/s. The new buoy will be deployed in the coming months and will provide accurate measurements of water quality parameters that are telemetered to the gage house for viewing in real-time by the public.

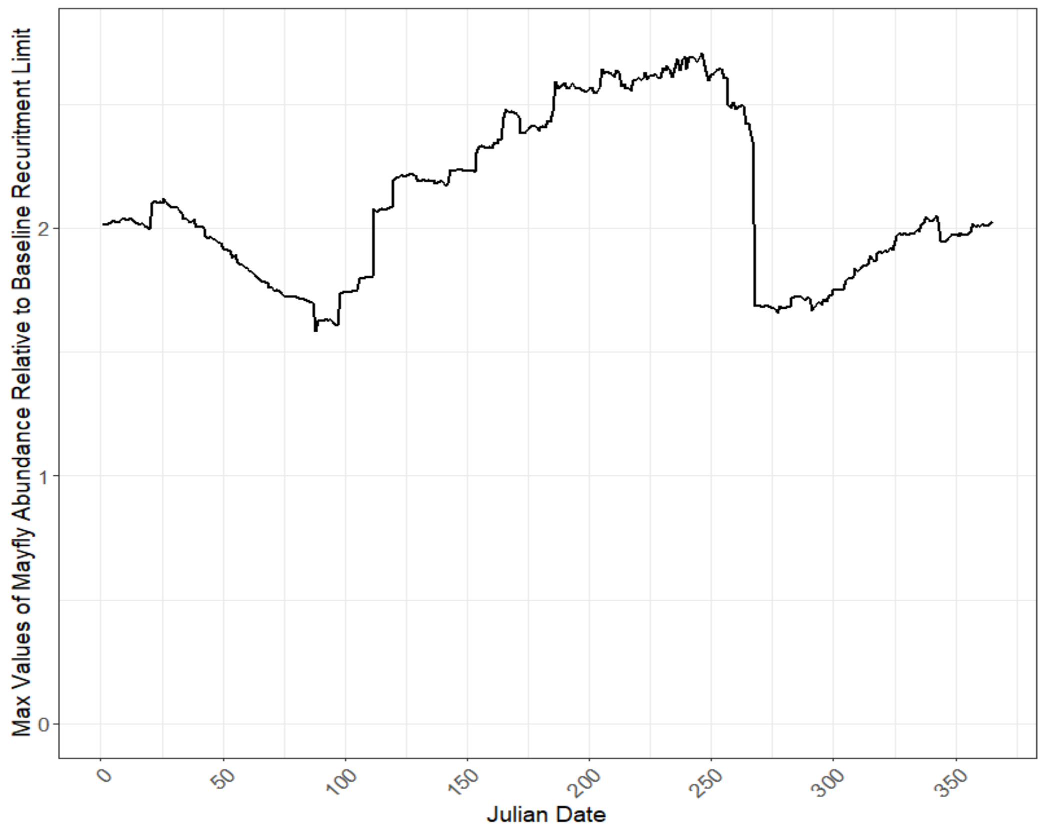

Figure O1. An example of invertebrate population model output showing how HFE timing (x-axis, Julian date 1 = January 1) affects mayfly population size (y-axis, relative abundance). In this simulation, the model was run 365 times, modeling an HFE on each day of the year. The line depicts the maximum mayfly population size over the annual cycle for an HFE that occurred on that Julian date. Mayfly populations respond most strongly (i.e., highest values of maximum abundance) to HFEs in spring or summer (i.e., Julian date ~100 to 225). In fall, mayfly response to HFEs is lower because mayfly demography prevents utilization of the event (i.e., there is less population growth at lower water temperatures during fall and winter). This is the expected profile for one species only; we expect different profiles for other aquatic invertebrate species. Figure courtesy of Angelika Kurthen, Oregon State University. Provisional data, subject to change.

Element O.2. Bank Erosion, Bed Sedimentation, and Channel Change in Western Grand Canyon

The objective of Project O.2 is to investigate how dam operations, including HFEs affect erosion and deposition of the riverbed in western Grand Canyon, focusing on the ~20-mile segment upstream from Pearce Ferry. A key part of this project is the collection of repeat surveys of the riverbed to quantify the magnitude and spatial distribution of changes in channel morphology associated with different dam operations. Data were collected before, during, and following the spring disturbance flow pulse in 2021, and those data were processed and presented at the annual reporting meeting in 2022. We delayed final reporting on these data, which was planned for 2023, to take advantage of the April 2023 HFE and collect another set of measurements. This effort consisted of three multibeam sonar surveys of the bed and lidar surveys of the subaerial banks before (April 25, 2023), during (April 27, 2023), and after (May 11, 2023) the HFE.

Repeat surveys of the channel bed were also conducted that will be used to estimate bedload transport in the study reach. Quality control checks on the bathymetric surveys are complete and the data are being processed. Processing of this data set will occur during FY 2024 with reporting on this data set occurring in the next work plan. We will present preliminary results that include results from both the 2021 and 2023 surveys at the annual reporting meeting in January 2024.

Element O.11. Decision Analysis

Low Lake Powell reservoir levels and anticipated low flows in the Colorado River below Glen Canyon Dam are creating unique resource management challenges. There is a significant amount of uncertainty related to these conditions and impacts to downstream resources. Understanding the impacts to resources downstream of Glen Canyon Dam with low surface elevations at Lake Powell, potentially dropping below power or dead pool, and the resource trade-offs required to avoid dropping below these elevations is of high priority. The original Flow Ad Hoc Group (FLAHG) charge, and the research proposed on Project O, was to 'evaluate opportunities for conducting higher spring releases that may benefit high-value resources of concern, fill critical data gaps, and reduce scientific uncertainties' (U.S. Department of the Interior, 2020). The low Lake Powell elevation has created challenges in meeting resource goals including moving water supply from the upper to lower basin, maintaining hydropower production, and minimizing the threat from warm-water invasive species.

The objective of Project O.11 is to develop modeling tools and analytical approaches to evaluate resource outcomes related to spring disturbance. However, the low reservoir elevation and possibility of sequential years of low-flows in the Colorado River, along with the directive by the Secretaries' designee to better understand resource management in these conditions, has led us to not only evaluate spring disturbance based on historical conditions, but also frame the decision problem to understand the dynamics between disturbance, resource trade-offs, and low reservoir elevations and low-flows. These steps will allow the GCDAMP to evaluate the trade-offs that occur between resources of concern, operational constraints under these conditions, and the importance of monthly volumes with respect to spring disturbance flows. Funding was provided to GCMRC to undertake Project O.11 late in FY 2022. The funding is being used to support the objective, including ongoing collaborations with researchers at Utah State University who are modeling future hydrology, operational alternatives, and electricity sector scenarios. Results are pending and will be presented in FY 2024.

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Project O Budget

Project O (funded by the C.5 Experimental Management Fund)							
Project O	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$93,211	$0	$0	$0	$0	$11,766	**$104,977**
Actual Spent	$47,988	$0	$43,564	$0	$0	$11,557	**$103,109**
(Over)/Under Budget	**$45,223**	**$0**	**($43,564)**	**$0**	**$0**	**$209**	**$1,868**

COMMENTS
FY23 Comments: - This project is funded entirely by the C.5 Experimental Management Fund on Reclamation's side of the GCDAMP budget. - The budgeted amount is left over funds from FY22 that went to salaries and the purchase of a new buoy system. - Underspent in salaries to offset the purchase of the buoy system. - Overspent in Operating Expenses due to the purchase of the buoy system.

Project O Deliverables: Is Timing Really Everything? Evaluating Resource Response to Spring Disturbance Flows

Presentations:

Lytle, D.A., Kurthen, A., and Freedman, J., 2023, Molecular and modeling tools for tracking food base dynamics in changing environments—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Appendix 1: Lake Powell Water Quality Monitoring

Program Manager (PM)	Bridget Deemer	**Principal Investigator(s)** (PI)	Bridget Deemer, USGS, GCMRC Tom Sabol, USGS, GCMRC Caitlin Andrews, USGS, GCMRC Bryce Mihalevich, USGS, GCMRC
Email	bdeemer@usgs.gov		
Telephone	360-606-4353		

Summary

Lake Powell received 13.42 million acre-feet (maf, 140% of the 1991-2020 average) of unregulated inflow in water year (WY) 2023. In comparison, inflow observed in WY 2022 was 6.1 maf (64% of the 1991-2020 average). At the end of WY 2023, Lake Powell's surface elevation was 3,573.6 feet (126 feet from full pool) with a storage of 8.79 maf, or 38% of live capacity. This is up from the end of WY 2022 when surface elevation was 3529.33 ft and storage was 5.80 maf. Releases for WY 2023 totaled 8.58 maf (as compared to 7 maf in WY 2022) consistent with operations under the 2007 Interim Guidelines (U.S. Department of the Interior, 2007). Operations for WY 2024 will fall under the Mid-Elevation Release Tier, and total projected annual release volume is currently 7.48 maf, with the October most probable (median) forecast projecting 9.4 maf of annual inflow to Lake Powell in WY 2024 (98% of average).

Glen Canyon Dam release temperatures reached their yearly maximum of 18.3 °C on October 20, 2023, which was about 3 degrees cooler than the maximum release temperature last year of 21.1 °C on September 22, 2022 (App1, Figure 1). Prior to 2022, the peak instantaneous water temperature measured at Lees Ferry had not exceeded 17.2°C in over 50 years. The warm-water temperatures in 2022 and 2023 are consistent with a recent trend wherein peak temperatures in Glen Canyon Dam releases have exceeded 15 °C in 6 of the 8 previous years. The warm waters pose serious concern for the establishment of smallmouth bass and other warm-water nonnative fish below Glen Canyon Dam (Bruckerhoff and others, 2022) as well as stressful conditions for the rainbow trout population in Glen Canyon (Korman and others, 2022). Specifically, when temperatures exceed 16 °C for extended periods of time, the likelihood that smallmouth bass and other warm-water nonnatives increase in abundance is much higher, while when temperatures exceed 20 °C for longer periods of time it is expected to negatively impact salmonids. Despite relatively cooler release temperatures than 2022, mean daily water temperature of dam releases was above 16 °C starting in mid-July and still has not dropped below 16 at the time of this report (November 13, 2023).

Still, the observed 2023 water release temperatures did not approach the historical pre-dam thermal regime (which ranged from near-freezing during winter months to 25-30 °C in summer months).

In the summer of 2023, layers of low dissolved oxygen (DO) water developed in all three major tributary arms of Lake Powell (Colorado, San Juan, and Escalante Rivers). Similar low DO events have developed in the past (namely in 2005, 2014, 2019, 2021, and 2022). This low DO was advected toward the forebay more rapidly than in other years given the large spring inflow volume, and dissolved oxygen in dam releases dropped below 5 mg/L starting 10 Jul (as compared with 3 Aug in 2022). Minimum DO concentration during the monthly water quality profiles was about 0.4 mg/L at 16 m depth in September 2023. This advection resulted in record low concentrations of DO in the Glen Canyon Dam tailwaters (minimum DO of 1.8 mg/L on October 1, 2023, as compared with 2.5 mg/L in September 2022 and 3.5 mg/L in 2005; App1, Figure 1, middle panel). Mean daily DO concentrations remained below 5 mg/L for 116 days (10 Jul through 3 Nov), as compared to 85 days in 2022 (from 3 Aug to 27 Oct), both of which represent sustained periods of low oxygen. The 2005 low DO event coincided with much lower recruitment and growth in the Lees Ferry rainbow trout fishery (Korman and others, 2012), so the low DO observed in Glen Canyon is of concern.

In the winter of 2022-2023, Lake Powell completely mixed. This resulted in higher-than-average conductivity in dam release waters (App1, Figure 1, lower panel). The large spring snowmelt also resulted in lower-than-average conductivity in dam releases during the summer months (App1, Figure 1, lower panel). The National Park Service continues to track and monitor the quagga mussel population throughout Lake Powell, mainly by estimating veliger densities in zooplankton tows.

FY 2023 Accomplishments

In fiscal year (FY) 2023, the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC) collected physical, biological, and chemical data from samples taken in Lake Powell, and at Glen Canyon Dam and Lees Ferry. This included 4 reservoir-wide surveys in collaboration with Reclamation as well as eight complete forebay surveys and two profile surveys before and after the April High-Flow Experiment (HFE; App1, Table 1-). USGS also checked, reprogrammed, and replaced temperature and conductivity loggers on a thermistor string that is deployed off the buoy line near Glen Canyon Dam in April of 2023.

A data paper, describing the long-term water quality monitoring data set, was published in early FY 2023 (Deemer and others, 2023). USGS also released an updated version of the long-term Lake Powell water quality data set that included all data collected in 2022 (Andrews and Deemer, 2023). This data set is a dynamic data release containing 8 comma separated (.csv) files (App1, Figure 2) structured so that it can be regularly updated with new data as it becomes available and undergoes QA/QC and normalization procedures (Andrews and Deemer, 2022).

During FY 2023, PI Deemer worked with Caitlin Andrews to develop a data visualization webpage for the Lake Powell Water Quality Monitoring Program (App1, Figure 2).

Several map visualizations for the webpage were developed collaboratively with Erica Byerly and Tom Gushue (see Project K for more information). The webpage will contain multiple visualizations summarizing real-time and long-term water quality data collected by the Bureau of Reclamation and USGS. This will include an interactive map, a time-series .gif demonstrating minimum and maximum water levels in the reservoir during its lifetime, and real-time water quantity and water quality plots. One visual we plan to include on the webpage was developed for the USGS-wide "chart challenge" (left panel on App1, Figure 2); it communicates how the current water level relates to the elevation of the reservoir spillway, regular water intake, and bypass structures and was viewed 4,200 time on social media. (https://twitter.com/USGS_Water/status/1697662438538113481).

Deemer and Andrews completed a data management plan to satisfy requirements for serving the webpage to the public. The webpage is still under development (mainly awaiting additional data scientist support from a position that still needs to be backfilled), but will hopefully link from the main Lake Powell webpage (https://www.usgs.gov/centers/southwest-biological-science-center/science/lake-powell-research).

In FY 2023, USGS also continued to maintain the sonde directly below Glen Canyon Dam for near-real-time data transmission to USGS GCMRC's Amazon Web Services platform. These data are then linked to Tableau, an online data visualization platform. The visualization was made public this fiscal year, with a provisional data statement noting that plots represent raw filtered values (see Project K for more information; Gushue and Thomas, 2022). An R shiny app and a python gui were also developed to query the postgres database directly for easier access to the underlying data (see Project K). Additional support is needed for the post-processing of these data given that the technician previously responsible for collecting and processing the data retired in June of 2023.

A postdoctoral researcher, Bryce Mihalevich, began working for GCMRC in June of 2022 with the goal of improving the Lake Powell CE-QUAL-W2 model. As of October 2022, a new grid structure had been developed that reflects a new bathymetric data set for Lake Powell (Jones and Root, 2021) and that performs under low reservoir water levels. This fiscal year, Mihalevich led the deployment of two weather stations in a relatively narrow and a relatively wide region of Lake Powell (the Escalante River confluence and Oak Canyon, respectively). These data will lead to a better understanding of meteorological processes near the water surface.

Mihalevich also consulted with Kathleen Holman at the Bureau of Reclamation Water Resources Engineering and Management Group to obtain existing meteorological data from Lake Powell (Holman and others, 2022). These data were used to modify evaporation equations within the CE-QUAL-W2 model.

Several additional model adjustments have been implemented and sensitivity testing is underway to identify the best modeling approach for water quality forecasting applications.

Deemer also continued model development and data analysis for a paper describing metalimnion dissolved oxygen dynamics in Lake Powell. The paper uses the long-term record of reservoir-wide dissolved oxygen profiles to model metalimnion dissolved oxygen concentration. Preliminary model results suggests that declining water levels interact with reservoir age to promote summer and fall metalimnion low dissolved oxygen events, with larger spring snowmelt inflows furthering dissolved oxygen declines.

We also conducted incubations to understand how both sediment source, monsoon inputs, and water temperature affect dissolved oxygen demand and nutrient cycling. Incubations showed that oxygen demand was highly temperature dependent in the two major inflows to the reservoir, the highest oxygen demand was from monsoonal inputs, and there was substantial phosphorus release from two of three sediment types. Our findings underscore how reservoir aging and dynamic hydrology can combine to reduce dissolved oxygen availability. A manuscript is currently being prepared for the journal Inland Waters discussing these efforts.

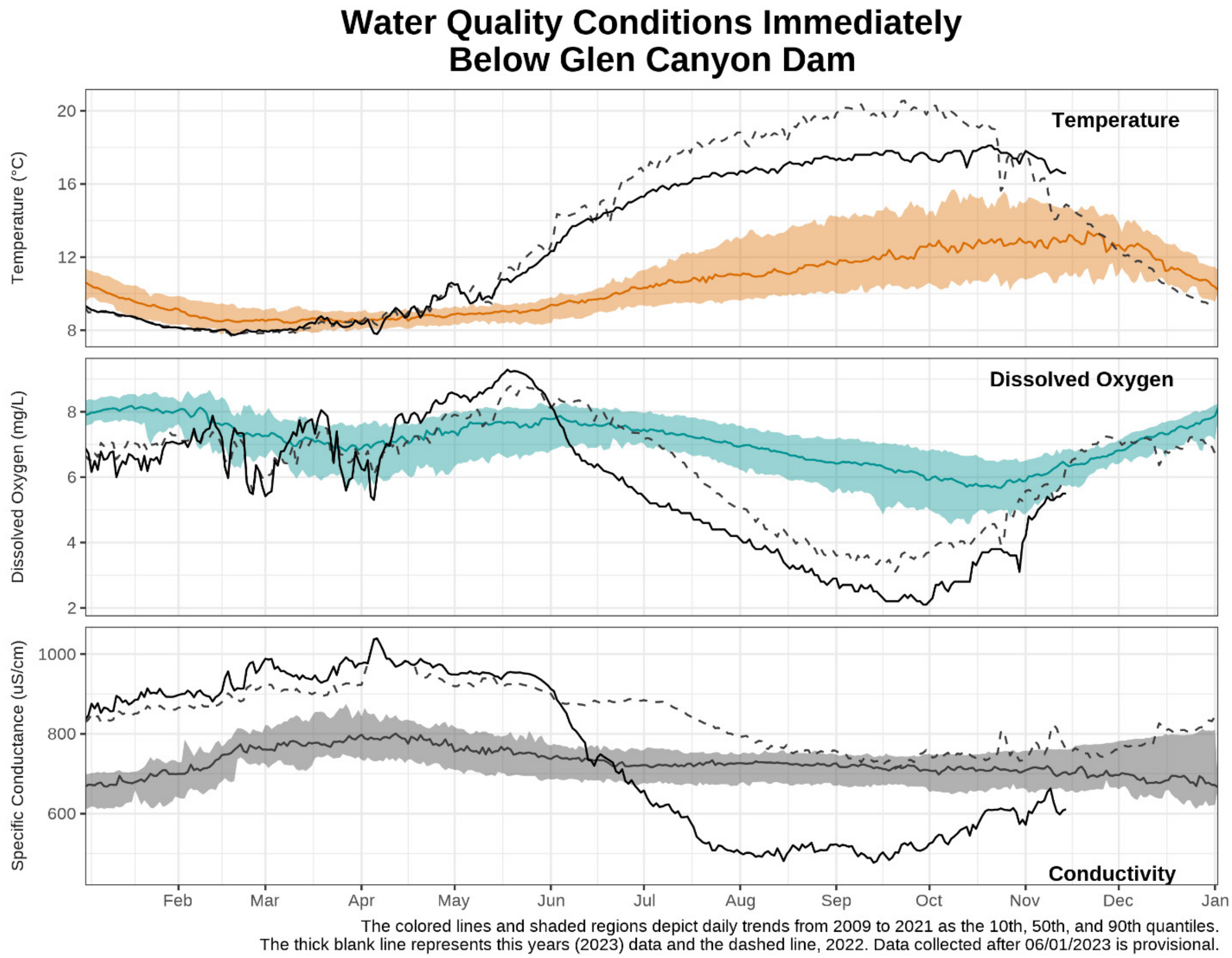
Funding Note:

The Lake Powell monitoring program was designed to determine status and trends of the water quality of Lake Powell and Glen Canyon Dam releases, determine the effect of climate patterns, hydrology, and dam operations on reservoir hydrodynamics and the water quality of Glen Canyon Dam releases, and provide predictions of future conditions. Since 1997, GCMRC has conducted a long-term water-quality monitoring program of Lake Powell and Glen Canyon Dam (GCD) releases in collaboration with the Bureau of Reclamation (Reclamation) and National Park Service (NPS).

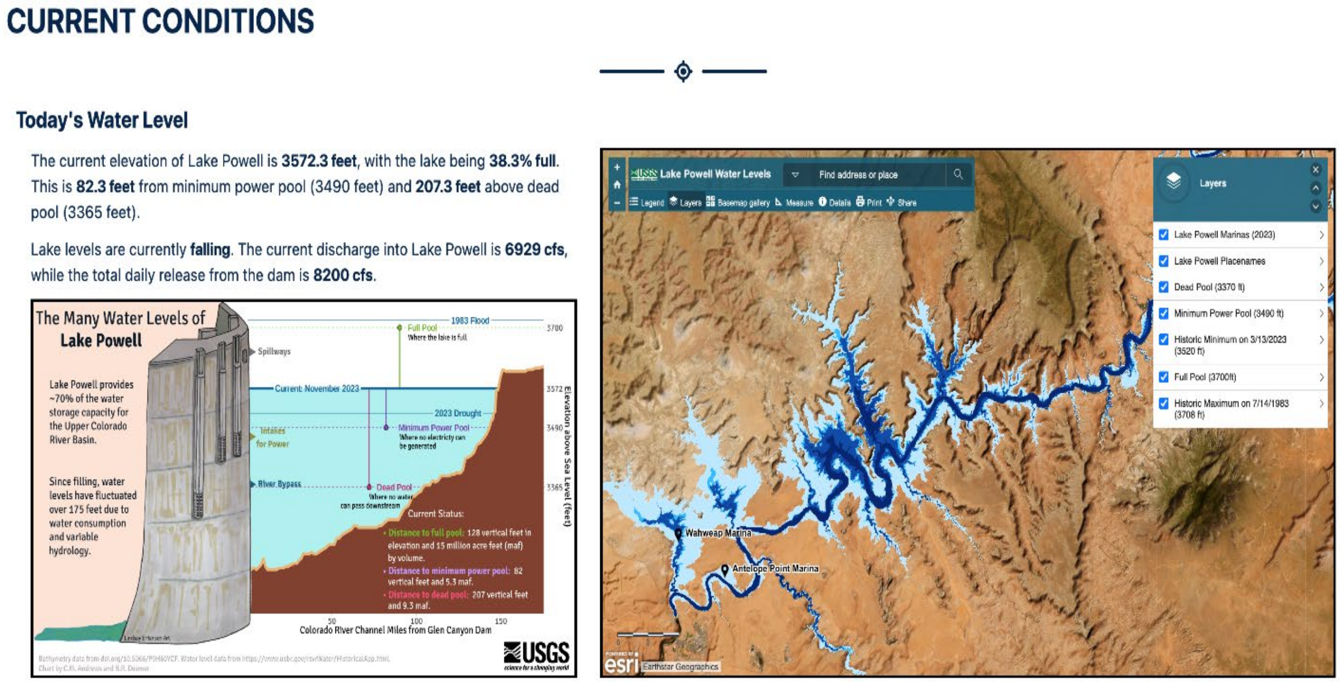
This project has been funded entirely by Reclamation from power revenues and receives no monetary support from the Glen Canyon Dam Adaptive Management Program (GCDAMP). In addition to direct funding of the program, Reclamation also provides support for laboratory analyses. A new interagency agreement was signed in FY 2023, which renews support for GCMRC involvement in the Lake Powell Water Quality Monitoring program over the next five years. In addition, in FY 2022 a separate scope of work was funded by Reclamation under the oversight of Clarence Fullard, titled "Leveraging Existing Data and Improving Existing Models to Better Bound Possible Water Quality Futures for Lake Powell and Its Tailwater." Funding for FY 2022 and FY 2023 was appended to the Interagency Agreement.

App1, Table 1. Beginning dates and sampling activity for the Lake Powell water-quality monitoring for FY 2023.

Date	Sampling Activity
10/18/22	Forebay, draft tubes, Lees Ferry
11/14/22	Forebay, draft tubes, Lees Ferry
12/05/22	Quarterly Survey
01/18/23	Forebay, draft tubes, Lees Ferry
02/13/23	Forebay, draft tubes, and Lees Ferry
03/06/23	Quarterly Survey
04/20/23	Pre-HFE profiles
04/24/23	Forebay, draft tubes, and Lees Ferry (during HFE)
05/4/23	Post-HFE profiles
05/09/23	Forebay, draft tubes, and Lees Ferry
06/15/23	Quarterly survey
07/11/23	Forebay, draft tubes, and Lees Ferry
08/11/23	Forebay, draft tubes, and Lees Ferry
09/07/23	Quarterly survey



App1, Figure 1. Water quality record from Glen Canyon Dam near Page, AZ (gage #09379901*) for temperature (upper panel) dissolved oxygen (middle panel) and specific conductance (lower panel). 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.



App1, Figure 2. Snapshot of the top of the draft data visualization webpage. The webpage will provide real time information about water levels in Lake Powell (left), an interactive map of Lake Powell surface area extent at different water levels (right; also described in Project K), and other visualizations that convey water quality and reservoir elevation information (including a real time version of App1, Figure 1 herein).

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Appendix 1 Budget

Appendix 1 - Lake Powell (NOT GCDAMP funded)

Total	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 20.481%	Total
Budgeted Amount	$276,904	$8,562	$32,483	$0	$0	$65,119	**$383,068**
Actual Spent	$218,622	$5,247	$54,062	$0	$0	$56,923	**$334,854**
(Over)/Under Budget	**$58,282**	**$3,315**	**($21,578)**	**$0**	**$0**	**$8,196**	**$48,214**

COMMENTS

FY23 Comments:
- This project is funded entirely by Reclamation with non-GCDAMP funding.
- Underspent Salaries is due to this agreement being on the calendar year rather than the fiscal year and additional salary will be spent by 12/31/2023.
- Underspent Travel & Training due to limited meetings and conferences attendance.
-Overspent Operating Expenses is for a Sonde and equipment purchase.

Appendix 1 Deliverables: Lake Powell Water Quality Monitoring

Presentations:

Deemer, B.R., 2023, Dams and drought: How Lake Powell and the southwest mega-drought have fundamentally altered downstream nutrient dynamics: Seminar at University of Nebraska, Lincoln.

Deemer, B.R., 2023, Dams and drought—How Lake Powell has altered downstream nutrient dynamics: Science Seminar at Washington State University, Vancouver.

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Journal Articles:

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Web Content and Applications:

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Appendix 2: Deliverables (Products), All Projects

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

Presentations:

Salter, G., Topping, D.J., Wright, S.A., Nelson, J.M., Mueller, E.R., and Grams, P.E., 2023, Numerical modeling of mud transport, storage, and release on the Colorado River, Arizona, *in* Proceedings of SEDHYD 2023, the Federal Interagency Sedimentation and Hydrologic Modeling Conference, St. Louis, Mo., May 8-12, 2023, https://www.sedhyd.org/2023Program/1/20.pdf.

Salter, G, Topping, D.J., Wright, S.A., Nelson, J.M, Mueller, E.R, Grams, P.E., 2023, The washload to bed-material load continuum—Transport, storage, and release of fine sediment in a large canyon-bound river: The 13th Symposium on River, Coastal, and Estuarine Morphodynamics, RCEM2023, Urbana-Champaign, Ill., September 25-28, 2023, https://uofi.box.com/s/58f97gz06sf490n4l9r6mfsmm7lxzihm.

Wood, M., Groten, J., Straub, T., Whealdon-Haught, D., Griffiths, R., Boldt, J.A., Lucena, Z., Brown, J., Suttles, S., and Dickhudt, P., 2023, State of the science and decision support for measuring suspended sediment with acoustic instrumentation, *in* Proceedings of SEDHYD 2023, the Federal Interagency Sedimentation and Hydrologic Modeling Conference, St. Louis, Mo., May 8-12, 2023, https://www.sedhyd.org/2023Program/1/15.pdf.

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Topping, D.J., Hazel, J.E., Jr., Kaplinski, M., and Grams, P.E., *In Press*, Resurvey of the Marble Canyon and Bridge Canyon dam sites in Grand Canyon National Park—Dam-induced changes in sediment storage and evidence supporting recent pre-dam bedrock incision: U.S. Geological Survey Professional Paper.

Griffiths, R.E., Topping, D.J., and Unema, J.A., *In Press*, Changes in sand storage in the Colorado River in Grand Canyon National Park from July 2017 through June 2020: U.S. Geological Survey Open-File Report.

USGS Data Releases:

None in FY 2023.

Web Applications:

http://www.gcmrc.gov/discharge_qw_sediment/

Stage, discharge, sediment transport, water-quality, and sand-budget data are served through the USGS-GCMRC website. The database associated with this website is updated every day to month depending on data type. This web-based application provides stakeholders, scientists, and the public with the ability to perform interactive online data visualization and analysis, including the on-demand construction of sand budgets and duration curves. These capabilities are unique in the world.

http://waterdata.usgs.gov/nwis

Stage, discharge, and water-quality data collected at 9 gaging stations by the USGS Utah and Arizona Water Science Centers under project are posted to this website every hour.

Project B Deliverables: Sandbar and Sediment Storage Monitoring and Research

Presentations:

Chapman, K.A., Grams, P.E., and Kaplinski, M.A., 2023, Effect of HFE frequency and dam Releases on sandbar deposition and erosion—presentation: Glen Canyon Dam Adaptive Management Program Meeting, Phoenix, Ariz., January 24-25, 2023.

Grams, P.E., Kaplinski, M.A., Kohl, K., and Sartain, S., 2021, A continuous high-resolution profile of the riverbed and water surface for 460-km of the Colorado River in Grand Canyon, Arizona—presentation: American Geophysical Union Fall Meeting, December 2022.

Grams, P.E., 2023, Project B overview and evaluation of High-Flow Experiments during aridification—presentation: Glen Canyon Dam Adaptive Management Program Meeting, Phoenix, Ariz., January 25, 2023.

Grams, P.E., 2023, Overview of Projects A, B, and L and evaluation of High-Flow Experiments during aridification—presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, Phoenix, Ariz., February 15, 2023.

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Grams, P.E., 2023, The future of high flows to rebuild sandbars in Grand Canyon—Will they ever happen again?: 2023 Guides Training Seminar sponsored by the Grand Canyon River Guides Association, Grand Canyon, Ariz., April 1, 2023.

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Kohl, K., 2023, How early ties to the National Spatial Reference System have advanced science, research, and decision making for management of the Colorado River—presentation: Civil GPS Service Interface Committee, Institute of Navigation Conference, Denver, Co., September 11-14, 2023.

Salter, G, Topping, D.J., Wright, S.A., Nelson, J.M, Mueller, E.R, Grams, P.E., 2023, Numerical modeling of mud transport, storage, and release on the Colorado River, Arizona—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Ariz., January 25, 2023.

Salter, G, Topping, D.J., Wright, S.A., Nelson, J.M., Mueller, E.R., and Grams, P.E., 2023, Numerical modeling of mud transport, storage, and release on the Colorado River, Arizona—presentation: Federal Interagency Sedimentation and Hydrologic Modeling Conference,. St. Louis, Mo., May 8-12, 2023, https://www.sedhyd.org/past/2023Proceedings/20.pdf.

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Web Applications:

Grand Canyon River Guides Adopt-a-Beach Photographs: http://www.gcmrc.gov/sandbar (https://grandcanyon.usgs.gov/gisapps/adopt-a-beach/index.html)

Remote Camera Sandbar Photographs: http://www.gcmrc.gov/sandbar (https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html)

Sandbar Monitoring Data: http://www.gcmrc.gov/sandbar (https://www.usgs.gov/apps/sandbar/)

Project C Deliverables: Riparian Vegetation Monitoring and Research

Presentations:

Butterfield, B., and Palmquist, E.C., 2023, Predictive vegetation modeling: Progress and opportunities for growth—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

Mihalevich, B., Deemer, B.R., Palmquist, E., and Kennedy, T, 2023, Science update—Lake Powell, riparian vegetation, and Bug Flows—virtual presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2023.

Palmquist, E.C., 2023, Colorado River plant communities below Glen Canyon Dam—presentation: Hakđagwi:va Chapter Arizona Native Plant Society meeting, Peach Springs, Ariz., June 2023.

Palmquist, E.C., 2023, Grand Canyon riparian vegetation, "Water in the West" Grand Valley State University seminar, Flagstaff, Ariz., May 2023.

Palmquist, E., Butterfield, B., and Sankey, J., 2023, Riparian vegetation monitoring and metrics—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

Palmquist, E.C., Ogle, K., Butterfield, B.J., Whitham, T.G., Allan, G.J., and Shafroth, P.B., 2023, Riparian plant occurrence and cover are differentially influenced by complex stressors and temperature interactions—presentation: Ecological Society of America Annual Conference, Portland, OR, August 2023.

Stevens, L.E., Palmquist, E.C., Fairley, H., and Sankey, J., 2023, Common reed (*Phragmites australis americanus*) ecology and responses to flow regulation along the Colorado River in Grand Canyon, Arizona, USA—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

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USGS Reports:

Palmquist, E.C. and Butterfield B.J., 2023, Project C: Riparian Vegetation Monitoring and Research, *in* Proceedings of the Fiscal Year 2022 Annual Reporting Meeting to the Glen Canyon Dam Adaptive Management Program, in Phoenix, Ariz., January 24-25, 2023: prepared by U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., 164 p., https://www.usbr.gov/uc/progact/amp/twg/2023-01-26-twg-meeting/20230126-AnnualReportingMeeting-ProceedingsFY2022AnnualReportingMeeting-508-UCRO.pdf.

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

Presentations:

Caster, J., Sankey, J.B., and Fairley, H., 2023, Monitoring for potential threats to Grand Canyon Rock Art—Preliminary observations and results at the Supai Man Petroglyph site—presentation: Long-term Experimental and Management Plan (LTEMP) Cultural Programmatic Agreement (PA) Meeting, October 2, 2023.

Caster, J., Sankey, J.B., and Fairley, H., 2023, Proposal to monitor C:06:0005 petroglyph site: Long-term Experimental and Management Plan (LTEMP) Cultural Programmatic Agreement (PA) Meeting, Phoenix, Ariz., April 11, 2023.

Caster, J., Sankey, J.B., Fairley, H., Pilkington, L., Boughter, D., Prophet, C., Bedford, A., Dierker, J. and Brennan, E., 2023, LTEMP vegetation management experiments to improve the geomorphic condition of archaeological sites in GRCA—preliminary results—poster for Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

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Fairley, H.C., Scott, M.L, and Fairley, A.H., 2023, Assessing 50 years of ecological changes at campsites along the Colorado River in Grand Canyon—Presentation: Glen Canyon Dam Adaptive Management Program Meeting, Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

Sankey, J.B., Fairley, H., and Caster, J.J., 2023, Preliminary field reports from the April High Flow Experiment—presentation: Glen Canyon Dam Adaptive Management Program, Technical Work Group Meeting, Flagstaff, Ariz., June 14, 2023, https://www.usbr.gov/uc/progact/amp/twg.html.

Sankey, J.B., Fairley, H., and Caster, J.J., 2023, Preliminary field reports from the April High Flow Experiment—Presentation: Glen Canyon Dam Adaptive Management Program, Adaptive Management Work Group Meeting, Flagstaff, Ariz., August 17, 2023, https://www.usbr.gov/uc/progact/amp/amwg.html.

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Sankey, J.B., Fairley, H., Caster, J.J., Dierker, J., Brennan, E., Pilkington, L., Bransky, N., and Kasprak, A., 2023, Archaeological sites are eroding in Grand Canyon owing to six decades of Glen Canyon Dam operations—Floods, low flows and vegetation management can help—presentation: Glen Canyon Dam Adaptive Management Program Meeting, Annual Reporting Meeting, Phoenix, Ariz., January 24-25, 2023.

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Williams-Grand Canyon News, January 17, 2023, Archeological sites in Grand Canyon National Park at risk. https://www.williamsnews.com/news/2023/jan/17/archeological-sites-grand-canyon-national-park-ris/

National Parks Traveler, March 31, 2023, Archaeological Sites In Grand Canyon Degrading Due To Glen Canyon Dam. https://www.nationalparkstraveler.org/2023/03/grand-canyons-archaeological-sites-degrading-due-glen-canyon-dam

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

Presentations:

Brown, P., Moody, E., Muehlbauer, J., Deemer, B., Yackulic, C., Corman, J., and Kennedy, T., 2023, The role of calcium carbonate in gross primary production in the Little Colorado River, AZ, and implications for humpback chub growth rates—presentation: Desert Fishes Council Annual Symposium, Bishop, Ca.

Deemer, B.R., 2022, Beyond eco-flows—Understanding biogeochemical links between limnology and management in human-made reservoirs—presentation: Joint Aquatic Science Meeting, Grand Rapids, Mich.

Deemer, B.R., 2023, Dams and drought—How Lake Powell and the southwest mega-drought have fundamentally altered downstream nutrient dynamics: Seminar at University of Nebraska, Lincoln.

Deemer, B.R., 2023, Dams and drought—How Lake Powell has altered downstream nutrient dynamics: Science Seminar at Washington State University, Vancouver.

Deemer, B.R., Reibold, R., Fatta, A., Corman, J., Yackulic, C.B., and Reed, S., 2022, Links between drought and river nutrition—Phosphorus export from Glen Canyon Dam under declining reservoir elevations—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, Flagstaff, Ariz.

Deemer, B.R. and Yackulic, C.B., 2022, Turning the red river green—An environmental flow increases primary productivity in the Colorado River—presentation: U.S. Geological Survey Friday Findings Seminar Series, https://www.usgs.gov/mission-areas/ecosystems/news/fridays-findings-january-14th-2022.

Dibble, K.L., 2023, Aquatic plants, food webs, and fish populations in the Colorado River in Glen Canyon Dam National Recreation Area: Outreach river trip and science presentation to the 2022 Native Youth Science Camp.

Dibble, K.L., Bruckerhoff, L.A., Yackulic, C.B., Schmidt, J.C., Bestgen, K.R., Kennedy, T.A., Mihalevich, B.A., Neilson, B.T., Wang, J., and Wheeler, K., 2022, Forecasting the influence of climate change, water storage decisions, and consumptive use on fishes of the Colorado River basin—virtual oral presentation and panel: DOI Turbine Talk Webinar Series focused on 'USGS Science on Climate Impacts on Hydropower.'

Dibble, K.L., Yard, M., Tusso, R., Buscombe, D., 2022, Aquatic vegetation in Glen Canyon—Observations following a spring disturbance flow—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, Phoenix, Ariz.

Hansen, L.E., and Yackulic, C.B., 2022, Linking ecosystem processes to consumer growth rates—Gross primary productivity and temperature drive fish growth—presentation: Joint Aquatic Science Meeting, Grand Rapids, Mich.

Journal Articles:

Deemer, B.R., Yackulic, C.B., Hall, R.O., Jr., Dodrill, M.J., Kennedy, T.A., Muehlbauer, J.D., Topping, D.J., Voichick, N., and Yard, M.D., 2022, Experimental reductions in sub-daily flow fluctuations increased gross primary productivity for 425 river kilometers downstream: PNAS Nexus, v. 1, no. 3, pgac094, https://doi.org/10.1093/pnasnexus/pgac094.

Deemer, B.R., Reibold, R.H., Fatta, A., Corman, J.R., Yackulic, C.B., and Reed, S.C., 2023, Storms and pH of dam releases affect downstream phosphorus cycling in an arid regulated river: Biogeochemistry, v. 165, p. 57–74, https://doi.org/10.1007/s10533-023-01064-5.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., 2023, Linking ecosystem processes to consumer growth rates—Gross primary productivity as a driver of freshwater fish somatic growth in a resource-limited river: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 9, p. 1456-1469, https://doi.org/10.1139/cjfas-2022-0229.

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Yard, M.D., Yackulic, C.B., Korman, J., Dodrill, M.J., and Deemer, B.R., 2023, Declines in prey production during the collapse of a tailwater rainbow trout population are associated with changing reservoir conditions: Transactions of the American Fisheries Society, v. 152, no. 1, p. 35-50, https://doi.org/10.1002/tafs.10381.

USGS Data Releases:

Deemer, B.R., Yard, M.D., Voichick, N., Goodenough, D.C., Bennett, G.E., Hall Jr., R.O., Dodrill, M.J., Topping, D.J., Gushue, T., Muehlbauer, J.D, Kennedy, T.A., and Yackulic, C.B., 2022, Gross primary production estimates and associated light, sediment, and water quality data from the Colorado River below Glen Canyon Dam: U.S. Geological Survey data release,

https://doi.org/10.5066/P9ZS6YLV.
Hansen, L.E., and Yackulic, C.B., 2022, Mark-recapture and environmental data used to predict flannelmouth sucker *(Catostomous latippinis*) growth rates within the Colorado River in the Grand Canyon from April 2012 to October 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9852I1G.
Korman, J., Yard, M., and Deemer, B.R., 2023, Rainbow trout growth data and growth covariate data from Glen Canyon, Colorado River, Arizona, 2012-2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9XU3SQP.
Reibold, R.H., Fatta, A., Voichick, N., Goodenough, D., and Deemer, B.R., 2023, Phosphorus, nitrogen, carbon, calcium, pH, and dissolved oxygen data from incubations of Colorado River water and sediment and associated ambient river water measurements: U.S. Geological Survey data release, https://doi.org/10.5066/P9L4JG9D.
Yackulic, C.B., Yard, M.D., Korman, J., Dodrill, M.J., and Deemer, B.R., 2022, Proximal and distal factors associated with the decline in secondary invertebrate prey production in the Colorado River, Glen Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9UZTYPV.

Project F Deliverables: Aquatic Invertebrate Ecology

Presentations:

Kennedy, T.A., 2023, Experimental bug flows increase algae production and insect diversity in the Colorado River, Grand Canyon: Annual River Guides Training Seminar, Marble Canyon, Ariz., April 2023.
Kennedy, T.A., 2023, Little bugs, big data, and Colorado River adaptive management—virtual presentation to Utah State University 'Colorado River' class, March 2023.
Kennedy, T.A., Muehlbauer, J., Metcalfe, A., Deemer, B., Ford, M., Szydlo, C., Behn, K., and Yackulic, C., 2023, Experimental bug flows enhance natural processes that sustain the Colorado River ecosystem—presentation: Glen Canyon Dam Adaptive Management Program, Technical Work Group meeting, Flagstaff, Ariz., June 2023.
Kennedy, T.A., Muehlbauer, J., Szydlo, C., and Metcalfe, A., 2023, Project F—Bug flows and food base update—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.
Kennedy, T.A., Mihalevich, B., Deemer, B., and Palmquist, E., 2023, Science update—Lake Powell, riparian vegetation, and bug flows—presentation: Glen Canyon Dam Adaptive Management Program, Adaptive Management Work Group meeting, Phoenix, Ariz., February 2023.
Lytle, D.A., Kurthen, A., and Freedman, J., 2023, Molecular and modeling tools for tracking food base dynamics in changing environments—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Metcalfe, A. and Fritzinger, C., 2023, River bats! Measuring bat activity along the Colorado River: Annual River Guides Training Seminar, Marble Canyon, Ariz., April 2023.

Metcalfe, A., and Kennedy, T., 2022, Community scientists shed light on aquatic foodwebs in Grand Canyon, Arizona, USA—Invited oral presentation for session on 'Uncertainty and error in hydrological citizen science observations': American Geophysical Union, Chicago, Ill.

Metcalfe, A., Kennedy, T., Muehlbauer, J., Starbuck, M., and Lytle, D., 2023. Evaluating bug flows—Phenology, diet, and growing conditions of a Hydropsychid caddisfly during a stable flow experiment—presentation: Society for Freshwater Science, Brisbane, Australia, May 2023.

Starbuck, M., Metcalfe, A., Muehlbauer, J., Lytle, D., and Kennedy, T., 2023, A deep dive on net-spinning caddisflies (*Hydropsyche oslari*)—poster presentation at Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Journal Articles:

Metcalfe, A.N., Fritzinger, C.A., Weller, T.J., Dodrill, M.J., Muehlbauer, J.D., Yackulic, C.B., Holton, P.B., Szydlo, C.M., Durning, L.E., Sankey, J.B., and Kennedy, T.A., 2023, Insectivorous bat foraging tracks the availability of aquatic flies (Diptera): The Journal of Wildlife Management, v. 87, no. 5, e22414, https://doi.org/10.1002/jwmg.22414.

Metcalfe, A.N., Muehlbauer, J.D., Ford, M.A., and Kennedy, T.A., 2023, Colorado River basin—chapter 11, in Delong, M., Jardine, T., Benke, A., and Cushing, C., eds., Rivers of North America: Cambridge, Mass., Academic Press, p. 463-509, https://www.elsevier.com/books/rivers-of-north-america/delong/978-0-12-818847-7.

Roe, C.C., Holiday, O., Upshaw-Bia, K., Benally, G., Williamson, C.H.D., Urbanz, J., Verocai, G.G., Ridenour, C.L., Nottingham, R., Ford, M.A., Lake, D.P., Kennedy, T.A., Hepp, C.M., and Sahl, J.W., 2023, Biting midges (Diptera: Ceratopogonidae) as putative vectors of zoonotic *Onchocerca lupi* (Nematoda: Onchocercidae) in northern Arizona and New Mexico, southwestern United States: Frontiers in Veterinary Science, v. 10, 1167070, https://doi.org/10.3389/fvets.2023.1167070.

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

Presentations:

Dzul, M.C., Yackulic, C.B., and Kendall, W.L., 2023, Can "true" survival be estimated without global resights? It depends on "true" movement—presentation: Euring 2023 Analytical Meeting & Workshop, Montpellier, France, April 19, 2023.

Journal Articles:

Bonjour, S.M., Gido, K.B., McKinstry, M.C., Cathcart, C.N., Bogaard, M.R., Dzul, M.C., Healy, B.D., Hooley-Underwood, Z.E., Rogowski, D.L., and Yackulic, C.B., 2023, Migration timing and tributary use of spawning flannelmouth sucker (*Catostomus latipinnis*): Journal of Fish

Biology, v. 103, no. 5, p. 1144-1162, https://doi.org/10.1111/jfb.15509.

Dibble, K.L., Yackulic, C.B., Bestgen, K.R., Gido, K.B., Jones, M.T., McKinstry, M.C., Osmundson, D., Ryden, D., and Schelly, R.C., 2023, Assessment of potential recovery viability for Colorado pikeminnow Ptychocheilus lucius in the Colorado River in Grand Canyon: Journal of Fish and Wildlife Management, v. 14, no. 1, p. 239–268, https://doi.org/10.3996/JFWM-22-031.

Dzul, M.C., Kendall, W.L., Yackulic, C.B., Van Haverbeke, D.R., Mackinnon, P., Young, K., Pillow, M., Rinker, P., and Thomas, J., *In Review,* Estimating migration timing and abundance in partial migratory systems by integrating continuous antenna detections with physical captures: Submitted to Journal of Animal Ecology.

Dzul, M.C., Yackulic, C.B., Giardina, M., Van Haverbeke, D.R., and Yard, M., 2023, Vital rates of a burgeoning population of humpback chub in western Grand Canyon: Transactions of the American Fisheries Society, v. 153, no. 4, p. 443-459, https://doi.org/10.1002/tafs.10415.

Dzul, M.C., Yackulic, C.B., and Kendall, W.L., *In Prep.,* Can “true” survival be estimated without global resights—It depends on “true” movement.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., 2023, Linking ecosystem processes to consumer growth rates—Gross primary productivity as a driver of freshwater fish somatic growth in a resource-limited river: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 9, p. 1456-1469, https://doi.org/10.1139/cjfas-2022-0229.

Van Haverbeke, D.R., Dzul, M.C., Yackulic, C.B., and Young, K.L., *In Prep*., Abundance estimation of a recent prodigious humpback chub population in western Grand Canyon.

USGS Data Releases:

Dzul, M.C., Yackulic, C.B., Giardina, M., Van Haverbeke, D.R., and Yard, M., 2023, Humpback chub (*Gila cypha*) capture histories and growth data for two areas in the Colorado River network from 2009-2022 and 2017-2022: U.S. Geological Survey data release, https://doi.org/10.5066/P9E96ADU.

Hansen, L.E., and Yackulic, C.B., 2023, Mark-recapture and environmental data used to predict flannelmouth sucker (*Catostomous latippinis*) growth rates within the Colorado River in the Grand Canyon from April 2012 to October 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9852I1G.

USFWS Reports:

Van Haverbeke, D.R., Newton, J., Young, K.L., Pillow, M.J., and Rinker, P.N., 2023a, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2022: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., U.S. Fish and Wildlife Service document no. USFWS-AZFWCO-FL-23-02, 53 p., https://www.fws.gov/sites/default/files/documents/Mark-Recapture%20and%20Fish%20Monitoring%20Activities%20in%20the%20Little.pdf.

Van Haverbeke, D.R., Rinker, P.N., and Pillow, M.J., 2023b, Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2022: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., U.S. Fish and Wildlife Service document no. USFWS-AZFWCO-23-05, 43 p.

Project H Deliverables: Salmonid Research and Monitoring

Presentations:

Yackulic, C.B., 2023, The times, They are a-changin'—Fish and the Grand Canyon: River Guides Training Seminar, Marble Canyon, Ariz.

Yackulic, C.B., Eppehimer D., Korman J., Giardina M., Yard M., Mihalevich B., Deemer B., Tennant L., and Schmidt, J., 2023, The Lees Ferry tailwater—Water quality, trout, and an uncertain future—virtual presentation: 14th Annual Native and Wild Trout Conference Phoenix, Ariz.

Yackulic, C.B., Saracco, J., Korman, J. and Dzul, M., 2023, Sharing abundance—Integrating long-term count data with short-term capture-recapture data in a marginalized, multistate Jolly-Seber framework—presentation: Euring Analytical Meeting, Montpellier, France.

Journal Articles:

Healy, B., Budy, P., Yackulic, C., Murphy, B.P., Schelly, R.C., and McKinstry, M.C., 2022, Exploring metapopulation-scale suppression alternatives for a global invader in a river network experiencing climate change: Conservation Biology, v. 37, no. 1, e13993, p. 1-18, https://doi.org/10.1111/cobi.13993.

Healy, B.D., Yackulic, C.B., and Schelly, R.C., 2022, Impeding access to tributary spawning habitat and releasing experimental fall-timed floods increases brown trout immigration into a dam's tailwater: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 3, p. 614-627, https://doi.org/10.1139/cjfas-2022-0231.

Korman, J., Deemer, B., Yackulic, C.B., Kennedy, T.A., and Giardina, M., 2022, Drought related changes in water quality surpass effects of experimental flows on trout growth downstream of Lake Powell reservoir: Canadian Journal of Fisheries and Aquatic Sciences, v. 80, no. 3, p. 424-438, https://doi.org/10.1139/cjfas-2022-0142.

Yard, M.D., Yackulic, C.B., Korman, J., Dodrill, M.J., and Deemer, B.R., 2023, Declines in prey production during the collapse of a tailwater rainbow trout population are associated with changing reservoir conditions: Transactions of the American Fisheries Society, v. 152, no. 1, p. 35-50, https://doi.org/10.1002/tafs.10381.

USGS Data Releases:

Korman, J., Yard, M., and Deemer, B.R., 2023, Rainbow trout growth data and growth covariate data from Glen Canyon, Colorado River, Arizona, 2012-2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9XU3SQP.

Project I Deliverables: Warm-Water Native and Nonnative Fish Research and Monitoring

Presentations:

Eppehimer, D.E., Yackulic, C.B., Bruckerhoff, L.A., Wang, J., Young, K.L., Bestgen, K.R., Mihalevich, B.A., and Schmidt, J.C., 2023, Drought, water storage, and an invasion—Designing responses to stop the spread of smallmouth bass in the Grand Canyon—presentation: American Fisheries Society, Grand Rapids, Mich., August 20-24, 2023.

Frye, E., and Ward, D.L., 2023, Common carp, uncommon predator—presentation: Colorado River Aquatic Biologists, Laughlin, Nev., January 4-5, 2023.

Frye, E., and Ward, D.L., 2023, Common carp, uncommon predator—presentation: Desert Fishes Council, St. George, Utah, November 16-20, 2023.

Ward, D.L., and Frye, E., 2023, Removal of invasive aquatic species using dissolved oxygen manipulation—presentation: Phoenix, Ariz., November 1, 2023.

Journal Articles:

Eppehimer, D.E., Yackulic, C.B., Bruckerhoff, L.A., Wang, J., Young, K.L., Bestgen, K.R., Mihalevich, B.A., and Schmidt, J.C., *In Review*, Failure to store—Low reservoir elevations spread non-native fish by increasing water temperature and propagule pressure: Submitted to Fisheries.

Project J Deliverables: Socioeconomic Research in the Colorado River Ecosystem

Presentations:

Bair, L., 2022, Adaptive management of regulated rivers—Eliciting indigenous knowledge and perspectives to inform monitoring and research—presentation: ACES session on knowledge and value pluralism, ACES: A Community on Ecosystem Services, Washington D.C., December 2022.

Bair, L., 2022, Panel chair, NEPA—Multiple Knowledge Systems: Plural ES Values & Environmental Justice ACES, A Community on Ecosystem Services, Washington D.C., December 2022.

Bair, L., 2022, Results of a Navajo Nation survey—Managing Glen Canyon Dam and the Colorado River in Grand Canyon—presentation: Navajo Nation Historic Preservation Department. November 2022, Window Rock, Ariz.

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., and Bair. L.S., *In Prep.*, The economic cost of designer flows in river conservation.

Hoelting, K.R., Martinez, D.E., Bair, L.S., Schuster, R.M., and Gavin, M.C., 2023, An opportunities framework for improved integration of cultural-benefits-knowledge in environmental decision-making: published on SocArXiv preprint server, submitted to Ecology and Society, https://doi.org/10.31235/osf.io/v6fxs.

Jungers, B., Abbott, J.K., and Bair, L.S., *In Prep*., Program evaluation of the Lees Ferry Brown Trout Incentivized Harvest Program.

Loomis, J.B., and Bair, L.S., 2023, Recreation use values for water-based recreation: Oxford Research Encyclopedia of Environmental Science, p. 1-35, https://doi.org/10.1093/acrefore/9780199389414.013.797.

Project K Deliverables: Geospatial Science and Technology

Presentations:

Gushue, T.M., Thomas, J.E., Andrews, C.M., 2023, Modernizing data telemetry efforts for important riparian resources in Grand Canyon—poster presentation: Glen Canyon Adaptive Management Program, Technical Work Group Annual Reporting Meeting, Phoenix, Ariz., January 22, 2023.

Thomas, J.E., and Gushue, T.M., 2023, Automating sensor-to-cloud workflows for riparian resources in Grand Canyon—poster presentation: U.S. Geological Survey, Community for Data Integration (CDI) Workshop, National Conservation Training Center, Shepherdstown, W.Va., May 5, 2023.

Science Communication Products:

Gushue, T.M., Thomas, J.E., Andrews, C.M., 2023, Advancing data telemetry capabilities using long range wide area network telemetry and the cloud sensor processing framework: Science Spotlight article published in the U.S. Geological Survey, Director's "Need to Know" blogpost, October 16, 2023.

Gushue, T.M., Thomas, J.E., Griffiths, R., 2023, SBSC's Grand Canyon Monitoring and Research Center Adds Low Earth Orbit (LEO) Satellite Dish to Historic Grand Canyon Sediment Gaging Station: U.S. Geological Survey online news article, April 14, 2023, https://www.usgs.gov/centers/southwest-biological-science-center/news/sbscs-grand-canyon-monitoring-and-research-center.

Code Development Products Maintained in Source Control (GitLab):

Byerley, E.B., 2023, Geospatial tools, *in* SBSC-GCMRC-GIS-Geospatial Tools Repository: https://code.usgs.gov/sbsc/gcmrc/gis/geospatial-tools

Byerley, E.B., 2023, Lake Powell visualization tools, *in* SBSC-GCMRC-GIS-Lake Powell Geospatial-Lake Powell Elevations + Extents Repository: https://code.usgs.gov/sbsc/gcmrc/gis/lake-powell-geospatial/lakepowell-elevations-extents

Thomas, J.E., 2023, Foundry PostgreSQL download tool, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/Foundry_PostgreSQL_Download_Tool?ref_type=headsab

Thomas, J.E., 2023, Grand Canyon machine learning camera, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/grand-canyon-machine-learning-camera

Thomas, J.E., 2023, NWIS data retrieval, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/NWIS_Data_Retrieval?ref_type=heads

Thomas, J.E., 2023, Short burst telemetry toolkit, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/tree/main/Short%20Burst%20Satellite%20Telemetry%20Toolkit?ref_type=heads

Thomas, J.E., 2023, Water quality IoT, *in* SBSC-GCMRC-IoT Gitlab Repository: https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/water-quality-iot-code

Online Content Maintained by Project:

Online Data Visualizations

Gushue, T.M, and Thomas, J.E., 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Daily water quality data at Glen Canyon Dam—online data visualization, last modified September 8, 2023, https://tableau.usgs.gov/views/colorado-river-water-quality-gcd/GlenCanyonDamSiteDailyAverages

Hensleigh, J., Andrews, C.M., Voichick, N., and Deemer, B., 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Lake Powell vertical water quality profiles—online data visualization, last modified December 18, 2022, https://tableau.usgs.gov/views/view-profiles-by-station-collection-date/ProfileByStationVisitDateDashboard

List of Websites and Web Applications

- Adopt-A-Beach Sites Photo Viewer: https://grandcanyon.usgs.gov/gisapps/adopt-a-beach/index.html
- Geospatial Services page (for advanced GIS users and developers): https://grandcanyon.usgs.gov/gisapps/restservices/index_wret.html
- Grand Canyon Geospatial Portal: https://grandcanyon.usgs.gov/portal/home/index.html
- Sandbar Monitoring Photo Viewer: https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html
- Updated Sandbar Monitoring Data website: https://www.usgs.gov/apps/sandbar/

Web Content on ESRI ArcGIS Online

- Access to Geospatial Data Holdings – ESRI's ArcGIS Online (Note: some content not shared to the public): http://usgs.maps.arcgis.com/home/search.html?q=GCMRC&t=content
- Predicted Shorelines for High Flows on the Colorado River Application: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=721001c63d91458883340f05c68c55f4

- River Campsite Web Application: https://usgs.maps.arcgis.com/home/item.html?id=0f9f6575bfee406cac6593b293883665

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

Presentations:

Sankey, J.B., Bransky, N., Durning, L., Gushue, T., Kohl, K., and Pigue, L.M., 2023, Overflight remote sensing in support of long-term monitoring and LTEMP—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, January 24-25, 2023, Phoenix, Ariz, https://www.usbr.gov/uc/progact/amp/twg.html.

Sankey, J.B., and Sankey, T., 2022, Measuring surface topography and vegetation changes in complex terrain with lidar and photogrammetry—presentation abstract: American Geophysical Union Fall Meeting, Chicago, Ill., v. 2022, p. GC15F-05, December 12-16, 2022.

Sankey, J.B., Sankey, T.T., Caster, J., and Debenedetto, G., 2023, Surface topography and vegetation changes from UAV and ground-based lidar data fusion—presentation abstract: IALE-North America 2023, Riverside, Calif., March 19-23, 2023.

USGS Data Releases:

Alfermann, A., Sankey, T.T., Bransky, N., and Sankey, J., *In Prep*., Vegetation and water classifications in 2009, 2013, and 2021 for a segment of the Paria River upstream of the Colorado River confluence, Arizona, USA: U.S. Geological Survey data release.

Sankey, J.B., Bransky, N., Pigue, L., and Kohl, K., *In Prep*., Four band image mosaic of the Colorado River corridor downstream of Glen Canyon Dam in Arizona derived from the May 2021 Airborne image acquisition: U.S. Geological Survey data release, to be published at https://doi.org/10.5066/P9BBGN6G.

Sankey, J.B., Kohl, K., Gushue, T., Bransky, N., Bedford, A., Durning, L., and Davis, P.A., *In Prep.,* DSMs for Colorado River Corridor in Grand Canyon National Park and Glen Canyon National Recreation Area—2002, 2009, 2013 and 2021 and DEM for 2021: U.S. Geological Survey data release.

Project N Deliverables: Hydropower Monitoring and Research

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., and Bair. L.S., *In Prep.,* The economic cost of designer flows in river conservation.

Project O Deliverables: Is Timing Really Everything? Evaluating Resource Response to Spring Disturbance Flows

Presentations:

Lytle, D.A., Kurthen, A., and Freedman, J., 2023, Molecular and modeling tools for tracking food base dynamics in changing environments—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting to the Technical Work Group, Phoenix, Ariz., January 2023.

Appendix 1 Deliverables: Lake Powell Water Quality Monitoring

Presentations:

Deemer, B.R., 2023, Dams and drought: How Lake Powell and the southwest mega-drought have fundamentally altered downstream nutrient dynamics: Seminar at University of Nebraska, Lincoln.

Deemer, B.R., 2023, Dams and drought—How Lake Powell has altered downstream nutrient dynamics: Science Seminar at Washington State University, Vancouver.

Deemer, B.R., 2022, Beyond eco-flows—Understanding biogeochemical links between limnology and management in human-made reservoirs—presentation: Joint Aquatic Science Meeting, Grand Rapids, Mich.

Journal Articles:

Deemer, B.R., Andrews, C.M., Strock, K.E., Voichick, N., Hensleigh, J., Beaver, J.R., and Radtke, R., 2023, Over half a century record of limnology data from Lake Powell, desert southwest United States: From reservoir filling to present day (1964–2021): Limnology and Oceanography Letters, v. 8, no. 4, p. 580-594, https://doi.org/10.1002/lol2.10310.

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Web Content and Applications:

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Appendix 3: Budgets, All Projects

Project A Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$499,029	$10,000	$59,600	$0	$396,277	$71,778	**$1,036,684**
Actual Spent	$520,763	$2,857	$107,074	$0	$398,187	$79,612	**$1,108,493**
(Over)/Under Budget	**($21,734)**	**$7,143**	**($47,474)**	**$0**	**($1,910)**	**($7,834)**	**($71,809)**

COMMENTS

FY23 Comments:
-Overspent Salaries during FY23 is due to shortfall in the budget for essential project staff.
-Underspent Travel & Training was from reluctance to attend AGU during December 2022 owing to COVID-19 and from delaying planned international travel until FY 2024.
-Overspent Operating Expenses was for instrument repairs and replacements initiated in Q4 FY22 that were completed in FY23.
-Overspending To other USGS Centers is due to rising costs for database/website design at Fort Collins and and EROS Science centers.

Project B Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$391,856	$4,500	$30,200	$393,512	$0	$65,650	**$885,718**
Actual Spent	$578,659	$11,450	$163,580	$8,000	$0	$95,378	**$857,067**
(Over)/Under Budget	**($186,803)**	**($6,950)**	**($133,380)**	**$385,512**	**$0**	**($29,728)**	**$28,651**

COMMENTS

FY23 Comments:
-Overspent Salaries is due to bringing staff on as USGS employees instead of contracting with Northern Arizona University.
-Overspent Travel & Training is due to more staff at GCMRC and expenses moved from the cooperaive agreement to internal.
-Overspent Operating Expenses is due to purchased equipment for bathymetric surveys, using funds saved from not needing to do the cooperative agreemnt.
-Underspent funds in Cooperative Agreements is due to personnel working on this project having left Northern Arizona University and the agreement is not continued.

Project C Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$136,566	$3,240	$3,310	$100,257	$0	$21,073	**$264,446**
Actual Spent	$125,031	$2,747	$5,910	$102,213	$0	$19,942	**$255,842**
(Over)/Under Budget	**$11,535**	**$493**	**($2,600)**	**($1,956)**	**$0**	**$1,131**	**$8,604**

COMMENTS

FY23 Comments:
-Underspent Salaries is due to ongoing issues with technician hiring.
-Underspent Travel & Training were to compensate for increased botanist costs.
-Overspent funds in Operating Expenses were due to contracting a boatman since planned in-house boatmen were unavailable.
-Overspent funds in Cooperative Agreements was due to increased costs for hiring botanists through NPS.

Project D Budget

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$204,799	$9,800	$3,223	$0	$0	$27,496	**$245,318**
Actual Spent	$199,686	$8,116	$9,938	$0	$0	$27,485	**$245,225**
(Over)/Under Budget	**$5,113**	**$1,684**	**($6,715)**	**$0**	**$0**	**$11**	**$93**

COMMENTS

FY23 Comments:
- Underspent Salaries is due to short delay in hiring.
- Underspent Travel & Training is due to postponed travel.
- Overspent amount in Operating Expenses is due to increase in publication costs and equipment replacement needs.

Project E Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$200,049	$10,500	$13,881	$0	$0	$28,330	**$252,760**
Actual Spent	$124,802	$3,102	$32,656	$0	$0	$20,268	**$180,829**
(Over)/Under Budget	**$75,247**	**$7,398**	**($18,775)**	**$0**	**$0**	**$8,062**	**$71,931**

COMMENTS

FY23 Comments:
- Underspent Salaries is due to HR-delays in hiring and staff turnover.
- Underspent Travel & Training is due to being understaffed and fieldwork and conference travel planned for FY23 was delayed.
- Overspent in Operating Expenses is for purchases of necessary lab equipment.

Project F Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$467,043	$17,039	$37,583	$0	$0	$65,850	**$587,515**
Actual Spent	$476,820	$12,720	$33,401	$0	$0	$66,011	**$588,952**
(Over)/Under Budget	**($9,777)**	**$4,319**	**$4,182**	**$0**	**$0**	**($161)**	**($1,437)**

COMMENTS

FY23 Comments:
- Overspent Salaries is due to promotions among staff and overtime associated with staff participation on the summer seining trip in support of fish diet studies.
- Underspent Travel & Training is due to emphasis on camping for Glen Canyon trips instead of lodging and only limited conference attenance.
- Underspent in Operating Expenses to offset seining trip and salary.

Project G Budget

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$328,681	$4,000	$51,900	$506,266	$0	$63,734	**$954,581**
Actual Spent	$288,754	$7,524	$42,976	$506,266	$0	$58,012	**$903,532**
(Over)/Under Budget	**$39,927**	**($3,524)**	**$8,924**	**$0**	**$0**	**$5,722**	**$51,049**

COMMENTS

FY23 Comments:
- Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Overspent in Travel & Training due to not budgeting costs associated with field work as travel.
-Underspent Operating Expenses is due to the bulk purchase of PIT tags through BOR.

Project H Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$147,413	$500	$24,066	$148,000	$0	$26,149	**$346,128**
Actual Spent	$109,795	$4,602	$90,474	$88,000	$0	$28,501	**$321,372**
(Over)/Under Budget	**$37,618**	**($4,102)**	**($66,408)**	**$60,000**	**$0**	**($2,352)**	**$24,756**

COMMENTS

FY23 Comments:
-Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Overspent in Travel & Training due to not budgeting costs associated with field work as travel.
- Overspent in Operating Expenses is due to change in funding mechanism for a cooperator from a Cooperative Agreement to a contract.
-Underspent amount in Cooperative Agreement is due to not funding a cooperative agreement and using staff to complete work.

Project I Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$220,574	$0	$7,100	$238,550	$0	$35,896	**$502,120**
Actual Spent	$264,539	$9,217	$66,235	$238,550	$0	$50,074	**$628,615**
(Over)/Under Budget	**($43,965)**	**($9,217)**	**($59,135)**	**$0**	**$0**	**($14,178)**	**($126,495)**

COMMENTS
FY23 Comments: - Overspent salaries is due to position turnover and an added Smallmouth Bass river trip in Oct 2022 (FY23). - Overspent in Travel & Training due to not budgeting costs associated with field work as travel and the added Smallmouth Bass river trip in Oct 2022 (FY23). -Overspent funds in Operating Expenses is for purchases of necessary lab equipment and field supplies and includes logistics costs for the Smallmouth Bass river trip in Oct 2022 (FY23).

Project J Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$126,530	$3,000	$1,500	$24,500	$0	$17,275	**$172,805**
Actual Spent	$103,013	$4,076	$36,474	$25,000	$0	$18,872	**$187,435**
(Over)/Under Budget	**$23,517**	**($1,076)**	**($34,974)**	**($500)**	**$0**	**($1,597)**	**($14,630)**

COMMENTS
FY23 Comments: - Underspent Salaries is due to change in mechanism for completing work with cooperators and contractors instead of salaried employees. - Overspent Travel & Training is due to rescheduled meetings and conferences post Covid-19. - Overspent funds in Cooperative Agreement is due to change in mechanism for completing work with cooperators and contractors.

Project K Budget

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$392,014	$3,500	$3,700	$0	$0	$50,393	**$449,607**
Actual Spent	$299,091	$5,862	$16,404	$0	$0	$40,565	**$361,921**
(Over)/Under Budget	**$92,923**	**($2,362)**	**($12,704)**	**$0**	**$0**	**$9,828**	**$87,686**

COMMENTS

FY23 Comments:
- Unspent Salaries is due to staff turnover and HR-delays in hiring of a Database Administrator and a Geographer.
- Overspent Travel & Training is due to rescheduled meetings and conferences post Covid-19.
-Overspent funds in Operating Expenses is for purchases of necessary information technology hardware and equipment for remote data collection and transmission.

Project L Budget

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$181,637	$0	$0	$80,596	$0	$25,346	**$287,579**
Actual Spent	$80,251	$0	$0	$99,269	$79,935	$13,108	**$272,563**
(Over)/Under Budget	**$101,386**	**$0**	**$0**	**($18,673)**	**($79,935)**	**$12,238**	**$15,016**

COMMENTS

FY23 Comments:
-Underspent Salaries is due to staff turnover in the previous year and change in mechanism for completing work.
-Overspent Cooperative agreements is due to change in mechanism to complete work from GCMRC staff to cooperator.
-Overspent To Other USGS Centers is due to the change in mechanism to complete work from GCMRC to other USGS center staff.

Project M Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$681,808	$20,000	$168,208	$0	$0	$109,822	**$979,838**
Actual Spent	$502,889	$16,462	$353,722	$0	$0	$110,208	**$983,281**
(Over)/Under Budget	**$178,919**	**$3,538**	**($185,514)**	**$0**	**$0**	**($386)**	**($3,443)**

COMMENTS
FY23 Comments: - Underspent Salaries is due to staff turnover, and USGS providing some funding for GCMRC leadership salaries. - Underspent Travel & Training was due to meetings and conference cancellations. - Overspent funds in Operating Expenses is due to hiring incentives, Information Technology, and rising costs for vehicle maintenance and fuel.

Logistics Budget

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$273,839	$3,000	$848,520	$11,000	$0	$142,384	**$1,278,743**
Actual Spent	$294,311	$168	$874,601	$48,350	$0	$149,023	**$1,366,453**
(Over)/Under Budget	**($20,472)**	**$2,832**	**($26,081)**	**($37,350)**	**$0**	**($6,639)**	**($87,710)**

COMMENTS
FY23 Comments: - Overspent Salaries is due to higher employee salaries and overtime. - Underspent funds for Travel & Training were due limited training and meetings attendance. - Overspent funds in Operating Expenses is due to rising costs of fuel and food. - Overspent funds in Cooperative Agreements is due to the Grand Canyon Youth cooperative agreement adding an annual trip for tribal youth.

Project N Budget

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$16,504	$1,500	$2,500	$0	$0	$2,588	**$23,092**
Actual Spent	$19,684	$0	$0	$0	$0	$2,485	**$22,169**
(Over)/Under Budget	**($3,180)**	**$1,500**	**$2,500**	**$0**	**$0**	**$103**	**$923**

COMMENTS

FY23 Comments:
-Overspending Salaries is due to higher employee salary and benfits costs.
-Underspent Travel & Training is due to planned travel through project J.
-Underspent funds in Operating Expenses was for software that was provided by USGS licensing at no cost to the project.

Budget Summary – Adaptive Management Program Total (without Lake Powell Agreement and without Project O)

Budget Summary Adaptive Management Program Total (without Lake Powell agreement)

Total	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.623%	Total
Budgeted Amount	$4,268,342	$90,579	$1,255,291	$1,502,681	$396,277	$753,762	**$8,266,932**
Actual Spent	$3,988,088	$88,902	$1,833,444	$1,115,648	$478,122	$779,544	**$8,283,749**
(Over)/Under Budget	$280,254	$1,677	($578,153)	$387,033	($81,845)	**($25,782)**	**($16,817)**

COMMENTS

FY23 Comments:
- Total overspent is due to the added Smallmouth Bass river trip in Oct 2022 through Project I (FY23).

Project O Budget

Project O (funded by the C.5 Experimental Management Fund)							
Project O	**Salaries**	**Travel & Training**	**Operating Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 12.623%**	**Total**
Budgeted Amount	$93,211	$0	$0	$0	$0	$11,766	**$104,977**
Actual Spent	$47,988	$0	$43,564	$0	$0	$11,557	**$103,109**
(Over)/Under Budget	**$45,223**	**$0**	**($43,564)**	**$0**	**$0**	**$209**	**$1,868**

COMMENTS

FY23 Comments:
- This project is funded entirely by the C.5 Experimental Management Fund on Reclamation's side of the GCDAMP budget.
- The budgeted amount is left over funds from FY22 that went to salaries and the purchase of a new buoy system.
- Underspent in salaries to offset the purchase of the buoy system.
- Overspent in Operating Expenses due to the purchase of the buoy system.

Appendix 1 Budget

Appendix 1 - Lake Powell (NOT GCDAMP funded)							
Total	**Salaries**	**Travel & Training**	**Operating Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 20.481%**	**Total**
Budgeted Amount	$276,904	$8,562	$32,483	$0	$0	$65,119	**$383,068**
Actual Spent	$218,622	$5,247	$54,062	$0	$0	$56,923	**$334,854**
(Over)/Under Budget	**$58,282**	**$3,315**	**($21,578)**	**$0**	**$0**	**$8,196**	**$48,214**

COMMENTS

FY23 Comments:
- This project is funded entirely by Reclamation with non-GCDAMP funding.
- Underspent Salaries is due to this agreement being on the calendar year rather than the fiscal year and additional salary will be spent by 12/31/2023.
- Underspent Travel & Training due to limited meetings and conferences attendance.
-Overspent Operating Expenses is for a Sonde and equipment purchase.