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Proceedings of the Fiscal Year 2022 Annual Reporting Meeting to the Glen Canyon Dam Adaptive Management Program

January 24-25, 2023, Phoenix, Arizona

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

Cover: Little Colorado River, Grand Canyon National Park
Photo by Lucas Bair, U.S. Geological Survey, Southwest Biological Science Center

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U.S. Geological Survey

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Introduction

Following is the U.S. Geological Survey (USGS), Southwest Biological Science Center (SBSC), Grand Canyon Monitoring and Research Center's (GCMRC), Proceedings of the Fiscal Year (FY) 2022 Annual Reporting Meeting to the Glen Canyon Dam Adaptive Management Program (GCDAMP). This proceedings report is prepared primarily for the Bureau of Reclamation to account for work conducted and products delivered by GCMRC and cooperators in FY 2022, and to inform the Technical Work Group of science activities[1] conducted in support of the Glen Canyon Dam Adaptive Management Program, as reported out during the Annual Reporting Meeting on January 24-25, 2023.

This document contains project reports for activities conducted in FY 2022[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 contains a report concerning USGS activities conducted as part of the Lake Powell Water-Quality Monitoring Program (Appendix 1). The Deliverables (Products) are presented at the end of the report, in Appendix 2, and project budgets are listed in each project and also compiled together as Appendix 3.

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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).

Persons, W.R., Ward, D.L., and Avery, L.A., 2015, Standardized methods for Grand Canyon fisheries research 2015 (ver. 1.1, January 2015): U.S. Geological Survey, Techniques and Methods, book 2, chapter A12, 19 p., https://www.usgs.gov/publications/standardized-methods-grand-canyon-fisheries-research-2015.

[2] This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information. 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 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

Low elevations in Lake Powell reservoir during FY 2022 contributed to this year being one marked by numerous extremes. Some notable extremes that were observed during FY 2022 included record high release temperatures (> 20°C, the warmest in over 50 years), record low concentrations of dissolved oxygen (< 5 mg/L measured immediately downstream of the dam from August 3 to October 27, 2022, a total of 85 days), and high captures of nonnative warm-water fish species across multiple monitoring projects.

In response to low reservoir elevations and numerous observations of nonnative warm-water species during FY 2022, two new compliance efforts were initiated, and GCMRC provided input, modeling, and other support to inform both of these compliance efforts (i.e., Supplemental Environmental Impact Statement for Near-term Colorado River Operations and Smallmouth Bass Environmental Assessment).

FY 2022 was also marked by a robust monsoon season and numerous floods on the Paria River, Little Colorado River, and other tributaries. The active monsoon season in FY 2022 created a positive sand mass-balance in Marble Canyon and favorable sediment conditions for testing a High-Flow Experiment (HFE), but an HFE was not ultimately approved in fall 2022 owing to a variety of factors including low Lake Powell reservoir elevations.

In FY 2022, GCMRC scientists and collaborators published numerous peer-reviewed journal articles, reports, and data releases. Below, we highlight one of the FY 2022 products that integrates research disciplines, spans multiple projects, and provides scientific findings from the Macroinvertebrate Production Flows, which were tested in FY 2022:

Deemer, B.R., Yackulic, C.B., Hall, R.O., Dodrill, M.J., Kennedy, T.A., Muehlbauer, J., Topping, D.J., Voichick, N., and Yard, M., 2022, Daily flow fluctuations associated with hydropower generation reduce gross primary productivity up to 400 kilometers downstream in a regulated river: Proceedings of the National Academy of Sciences NEXUS, v. 1, p. 1–12, https://doi.org/10.1093/pnasnexus/pgac094.

> Summary: Algae production fuels many river food webs including those of the Colorado River. This paper compares rates of algae production downstream of Glen Canyon Dam during load following hydropower operations to those during experimental Bug Flows in 2018 and 2019. The paper demonstrates increased algae production during Bug Flows (weekend) water throughout the 425-kilometer-long segment of Colorado River compared to fluctuating flows during weekdays. Rates of algae production during steady-low flows were 41% higher than during load following flows, mostly owing to large reductions in sediment-driven turbidity. We estimate that experimental Bug Flows increased springtime carbon fixation by 0.27 g C m^{-2} d^{-1}, which is ecologically meaningful considering median C fixation in 356 US rivers of 0.44 g C m^{-2} d^{-1} and the fact that native fish populations in the Colorado River are food-limited.

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.	**Project D** examines 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 CRe, 2) monitoring changes in riparian vegetation using field-collected data and digital imagery, 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 E, F, G, I, and J** through 1) 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, 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 mainstem 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.

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.

Recreational Experience

LTEMP Resource Goal	Project
Maintain and improve the quality of recreational experiences for the users of the CRe. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.	Addressed by **Projects B, C, and H** through 1) 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, 2) monitoring changes in riparian vegetation using field-collected data and digital imagery, 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 increase understanding of key factors such as density and recruitment, prey availability, and variables that control the abundance and growth of the trout population.

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 E, F, G, and I** through 1) 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, 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 mainstem 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 and B** 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 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.

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.

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 H, E, F, and G** through 1) monitoring the status and trends of both rainbow and brown trout upstream of Lees Ferry in Glen Canyon as well as increase 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 CRe 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 mainstem 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 F, I, G, 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 CRe from Lees Ferry to Lake Mead, 3) monitoring of humpback chub populations, dynamics, and condition in aggregations in the mainstem 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 **Project C** through monitoring changes in riparian vegetation using field-collected data and digital imagery, 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

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	**D.1/D.2**	**A.2 E.1-3 F.1-4**	**G.1-6 I.1 J.1**	**N.1**	**G.1-6 I.1**	**A.1/A.3 B.1/B.2 J.1/J.3**	**A.1/A.3 B.1/B.2/B.3 D.3**	**D.3**	**H.1/H.2/H.4 I.1**	**H.3 I.1-3**	**C.1/C.2/C.3**
Fall High-Flow Experiments (HFE) > 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	**D.1/D.2**	**A.2 E.1-3 F.1/F.2**	**G.1-6 J.1**	**N.1**	**G.1-6 I.1**	**A.1/A.3 B.1/B.2/B.6 J.1/J.3**	**A.1/A.3 B.2/B.6**		**H.1/H.2/H.4**	**H.3 I.1-3**	**C.1/C.2/C.3**
Fall HFE ≤ 96-hr ≤ 45,000 ft³/s, in Oct. or Nov.	**D.1/D.2**	**A.2 E.1-3 F.1/F.2**	**G.1-6 J.1**	**N.1**	**G.1-6 I.1**	**A.1/A.3 B.1/B.2/B.6 J.1/J.3**	**A.1/A.3 B.2/B.6**		**H.1/H.2/H.4**	**H.3 I.1-3**	**C.1/C.2/C.3**
Humpback chub translocation			**G.7**								
Larval humpback chub head-start program			**G.7**								
Macroinvertebrate production flows		**F.1/F.2/F.4**	**F.4 G.1-6 J.1**	**N.1**	**F.4 G.1-6 I.1**	**J.3**			**F.4 H.1/H.2/H.4**	**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	**D.1/D.2**	**A.2 E.1-3 F.1/F.2**	**G.1-6 J.1**	**N.1**	**G.1-6 I.1**	**A.1/A.3 B.1/B.2/B.6 J.1/J.3**	**A.1/A.3 B.2/B.6**		**H.1/H.2/H.4**	**H.3 I.1-3**	**C.1/C.2/C.3**
Riparian vegetation restoration	**D.1/D.2**					**C.4 J.1/J.3**					**C.4**
Spring HFE ≤ 45,000 ft³/s, in March or April	**D.1/D.2**	**A.2 E.1-3 F.1/F.2**	**G.1-6 J.1**	**N.1**	**G.1-6 I.1**	**A.1/A.3 B.1/B.2/B.6 J.1/J.3**	**A.1/A.3 B.2/B.6**		**H.1/H.2/H.4**	**H.3 I.1-3**	**C.1/C.2/C.3**
Trout management flows				**N.1**					**H.1/H.2/H.4**	**H.3**	**C.1/C.2/C.3**
Spring disturbance flow	**O.3**	**O.1/O.5**	**O.7**	**O.9**	**O.7**	**O.8/O.10**	**O.2/O.10**	**O.2**	**O.6**	**O.6**	**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
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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 mainstem and 16 tributary sites located throughout the CRe. These data are used to inform managers about the physical status of the Colorado River in the CRe and how this physical status is affected by dam operations in near real time. 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

The results and hypothesis testing described below are completed via the 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 Work Plan for additional information on this and the other elements of Project A listed herein.

Project Elements

Element A.1. Stream Gaging and Hydrologic Analyses

Element A.1 partially funds the collection, serving, and interpretation of continuous 15-minute measurements of stage and discharge on the mainstem 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

Element A.2 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 mainstem 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

Element A.3 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 sediment transport.

There are two key hypotheses that guide the monitoring and research conducted under the three elements of Project A. Owing to the interlocking nature of the three elements, the hypotheses that guide Project A and the results from Project A cannot be easily segregated by element and are described together in this section.

- **Hypothesis 1:** Glen Canyon Dam can be operated such that the sand resources in the CRe are sustainable. Sustainable management of sand requires that sandbars and other high-elevation sandy deposits be maintained or increased while not depleting the overall amount of sand in the CRe.
- **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.

These hypotheses are paraphrased from the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS; U.S. Department of Interior, 2016a, b) and from earlier goals, information needs, and strategic science questions formulated by the Glen Canyon Dam Adaptive Management Program (GCDAMP).

The results from Project A during FY 2022 highlighted below are provided in two journal articles, three USGS reports (one published, one in layout at the USGS Science Publishing Network, and one in review), and two updated web applications described in the list of Deliverables below. Much of the monitoring data collected by this project, including those required to trigger, design, and evaluate a potential November 2022 HFE, were collected and posted to the project web application (https://www.gcmrc.gov/discharge_qw_sediment/). The sand supplied by the Paria River during the summer 2022 sand-accounting period (~1.5 million metric tons) was the second largest of any period where a fall HFE was considered.

Because of the laboratory slow-down caused by a change in Project A's funding structure between the previous TWP and the FY 2021–23 TWP, the laboratory analyses of many suspended-sediment samples from FY 2022 remain incomplete. Thus, unlike in years prior to 2021, when this problem first arose, it will be relatively late in the subsequent fiscal year (FY 2023 in this case) when we post the final sediment data on Project A's website. Given the multifaceted nature of Project A, only a few key results are listed herein.

- A USGS Open-File Report submitted for review during FY 2022 (Griffiths and others, in review) analyzing changes in sand storage during sediment years 2018–2020 (July 1, 2017, through June 30, 2020) 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 extends the sediment-year 2003–2017 analyses in Topping and others (2021) through sediment year 2020; this report is now in USGS review with anticipated publication in 2023. 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).

- Gross primary production was increased throughout the CRe through reductions in daily flow fluctuations at Glen Canyon Dam (Deemer and others, 2022, Proceedings of the National Academy of Sciences NEXUS). The reduction in both silt and clay concentration and sand concentration caused by such reductions in the daily range in discharge released from the dam led to reduced turbidity, and therefore greater gross primary production throughout the ~425-km length of the CRe.

- A USGS Professional Paper (Topping and others, in press at the USGS Science 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 at least ~24 million metric tons of sand erosion from Marble Canyon between the 1963 closure of Glen Canyon Dam and 2017, mostly during ~3–4 periods of higher dam releases (Topping and others, 2021). This result provides further support for the conclusions of Topping and others (2021) that indicate that it remains unclear if sand can be sustainably managed in the CRe utilizing the available tributary supply of sand. 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.

- Although an earlier study showed the presence of a slight positive bias in both suspended-sand concentration and grain size in measurements made by the depth-integrating suspended-sediment samplers used at the gaging stations in the CRe (Sabol and Topping, 2013), further evaluation indicated that this sampler can collect unbiased suspended-sand data in the Colorado River (Sabol and others, 2022). This result helps inform the uncertainty in the continuous mass-balance sand budgets at http://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP.

- 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, in press, Water Resources Research). 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 used to design HFEs and evaluate the effect of dam operations on sand resources (Topping and others, 2021; Griffiths and others, in review).

- During FY 2022, the following changes in sand mass (shown in tabular form in Table 1) occurred in the six reaches where continuous mass-balance sand budgets are constructed by Project A. Sand accumulated in all five reaches of the CRe between Lees Ferry and Diamond Creek during FY 2022. The changes in sand mass in this table are preliminary and will likely change because we still have a large backlog of suspended-sediment samples to process (caused by a laboratory slow-down arising from funding issues and a USGS hiring slowdown). Data from (http://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP).

Table 1. Changes in sand mass during FY 2022 (preliminary results, do not cite)

Reach	Change in sand mass in metric tons during FY 2022; interpretation of change in bold uses criteria in Topping and others (2021)
Upper Marble Canyon	1,200,000±430,000 **Deposition**
Lower Marble Canyon	440,000±65,000 **Deposition**
Eastern Grand Canyon	430,000±300,000 **Deposition**
East-Central Grand Canyon	180,000±160,000* **Deposition**
West-Central Grand Canyon	410,000±93,000* **Deposition**
Western Grand Canyon and the Lake Mead Delta (Colorado River downstream from Diamond Creek)	470,000±23,000** **Deposition**

*Data used to compute these values end in late August 2022 because the Colorado River above National Canyon n the Supai, AZ, gaging station had not been visited since August 30 at the time this report was completed.

**Data used to compute these values end in late early September 2022 because of instrument problems at the Colorado River above Diamond Creek near the Peach Springs, AZ, gaging station that will remain unresolved until backlogged suspended-sediment samples from this station get processed through the laboratory during FY 2023. These samples accumulated in the laboratory owing due to a USGS hiring slowdown.

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

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Project A Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$485,907	$10,000	$58,500	$0	$392,587	$68,336	**$1,015,330**
Actual Spent	$497,227	$2,431	$83,030	$0	$459,407	$71,822	**$1,113,917**
(Over)/Under Budget	**($11,320)**	**$7,569**	**($24,530)**	**$0**	**($66,820)**	**($3,486)**	**($98,587)**
FY21 Unspent Funds	**$135,000**					**FY22 Unspent Funds**	**$36,413**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent funds; etc.)*

FY22 Comments:
-Overspent Salaries during FY22 is due to shortfall in the budget for essential project staff.
-Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
-Overspent Operating Expenses was for instrument repairs and replacements initiated in Q4 FY22 that will be 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:

Because the COVID-19 pandemic is only now ending, no presentations were made at professional scientific meetings during FY 2022. One presentation was made to the GCDAMP at the January 2022 Annual Reporting Meeting.

Journal Articles:

Deemer, B.R., Yackulic, C.B., Hall, R.O., Dodrill, M.J., Kennedy, T.A., Muehlbauer, J., Topping, D.J., Voichick, N., and Yard, M., 2022, Daily flow fluctuations associated with hydropower generation reduce gross primary productivity up to 400 kilometers downstream in a regulated river: Proceedings of the National Academy of Sciences NEXUS, v. 1, p. 1–12, https://doi.org/10.1093/pnasnexus/pgac094.

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USGS Reports:

Sabol, T.A., Topping, D.J., Griffiths, R.E., and Dramais, G., 2022, Field investigation of sub-isokinetic sampling by the US D-96-type suspended-sediment sampler and its effect on suspended-sediment measurements: U.S. Geological Survey Open-File Report 2022-1077, 14 p., https://doi.org/10.3133/ofr20221077.

Topping, D.J., Hazel, J.E., Jr., Kaplinski, M., and Grams, P.E., *in press* at the USGS Science Publishing Network, 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 review*, 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.

Web Applications:

https://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 has been maintained to provide 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.

https://waterdata.usgs.gov/nwis

Stage, discharge, and water-quality data collected at 9 gaging stations by the USGS Utah and Arizona Water Science Centers 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
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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 with respect to 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 volumes and campsite areas. 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 2021 were presented at the Annual Reporting Meeting in January 2022, and the most recent data, collected in October 2022, will be presented at the Annual Reporting Meeting in January 2023.
Images from the remote cameras were retrieved in October 2021, February 2022, and October 2022. 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 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 (Figure 1). 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 have experienced erosion, much of the HFE-deposited sand has persisted. Deposition of sand during HFEs has resulted in temporary increases in campsite area; however, there has been 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).

In addition to the gradual erosion that typically follows deposition associated with HFEs (Hazel and others, 2010), many sandbars in Marble and Grand Canyons experienced dramatic episodes of erosion in 2021 and 2022 during summer thunderstorms. Hillslope runoff during these events resulted in the formation of gullies and deposition of debris on sandbar campsites (Figure 2). Similar damage caused during previous monsoon seasons was repaired by HFEs, which bury debris and fill gullies (Grams and others, 2018).

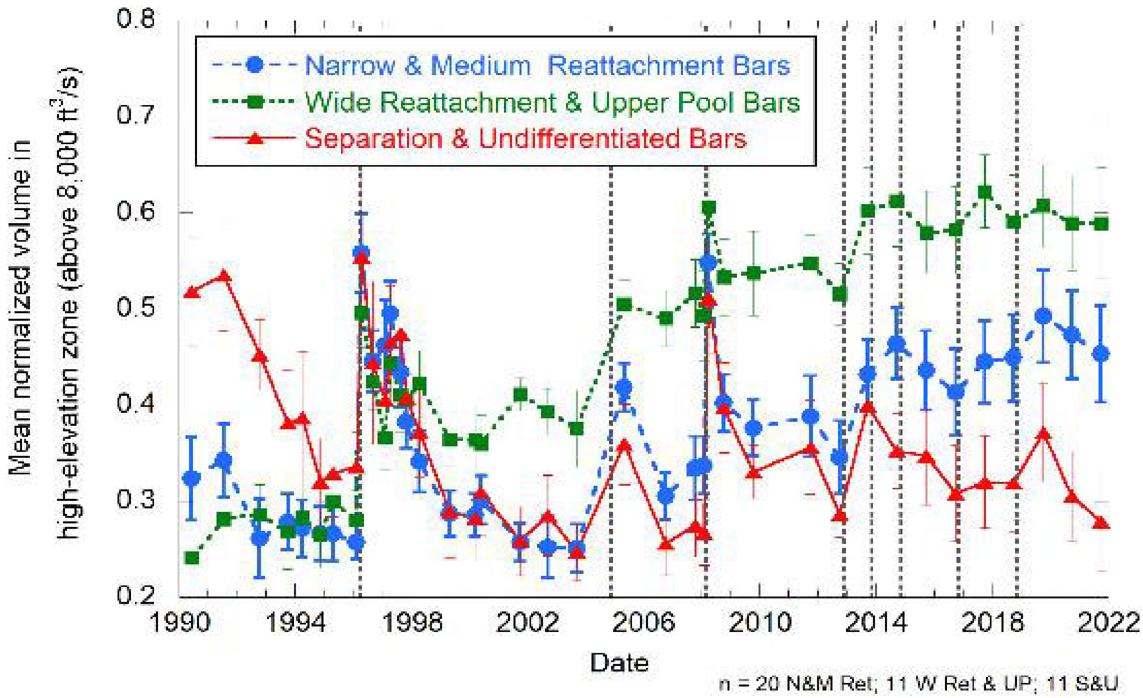

Figure 1. Normalized sandbar volume June 1990 to October 2021 for each site type. Methods and normalization procedure are described by Hazel and others (2022). Error bars are standard error. Vertical dashed lines show the timing of HFEs. Sites were measured immediately following HFEs in 1996, 2004, and 2008 only. Beginning in 2009, measurements were made once annually in October. The HFEs have continued to result in deposition and sandbar measurements indicate that there has been some net increase in sandbar volume since the beginning of the HFE protocol in 2012 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. Please see https://www.usgs.gov/apps/sandbar/sites for site locations and most recent data for individual sites.

Figure 2. Photographs looking downstream at a sandbar campsite downstream from Tatahatso Wash at river mile (RM) 37.9 in Marble Canyon taken October 3, 2020 (left), and October 4, 2022 (right). Note person for scale. The erosion and deposition of debris occurred during a high-intensity summer thunderstorm on July 14, 2021. The sand routing model (Wright and others, 2010) and the recently completed sandbar volume model (Mueller and Grams, 2021) were used to design the hydrograph and evaluate potential outcomes during the planning process for a potential fall 2022 HFE. The models were also used to illustrate for the technical team the relative importance of HFE magnitude and duration (Figure 3).

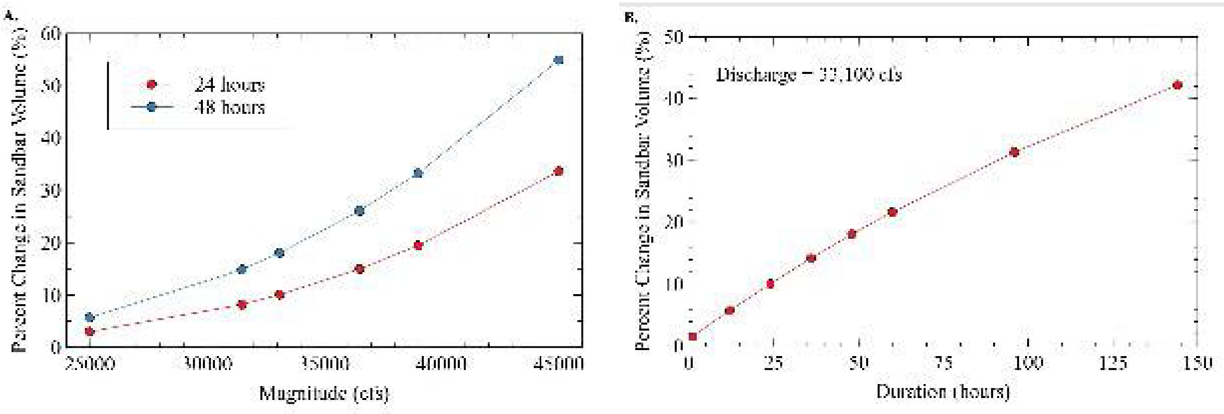

Figure 3. Predicted changes in sandbar volume for potential HFEs of different magnitude and duration using the Mueller and Grams (2021) sandbar volume model. (A) For potential HFEs of both 24-hour and 48-hour duration, magnitude has a strong control over deposition because it controls potential deposit size by inundating more area. This physical control on bar deposition is consistent with observations and modeling results from the 1996 HFE (Hazel and others, 2022). A relatively low-magnitude HFE of ~33,100 ft^3/s is predicted to be about one-third as effective as a 45,000 ft^3/s HFE. (B) Duration is secondary to frequency, but also important because time is needed for sand concentrations to increase and for sand to be redistributed within eddies. A relatively short-duration 24-hour HFE predicted to be about one-third as effective as a 96-hour HFE.

While HFEs have resulted in sandbar deposition and net increases in sandbar volume, campsite area has remained stable or decreased 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). Vegetation expansion consisted mostly of tamarisk between 2002 and 2009 and seep willow between 2009 and 2013 (Durning and others, 2021). Vegetation removal is being conducted experimentally by National Park Service personnel at three of the long-term sandbar monitoring sites. We will be monitoring the effect of vegetation removal on deposition and erosion for those sites.

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 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 of sediment storage change 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).

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, sediment storage changes over long time periods (many years or decades) can be computed accurately and with well-constrained uncertainty.

During FY 2022, we completed processing of data collected in 2019 lower Marble Canyon (River Miles (RM) 29 to 61) and eastern Grand Canyon (RM 61 to 87), data collected for Spring Disturbance Flow (SDF), and data collected during the 2021 overflight. Data sets from these mapping efforts and reports describing the results will be completed in FY 2023. A new channel mapping data set was collected in April 2022 for west central Grand Canyon (RM 87-166). This effort consisted of 64 topographic surveys, 143 total station setups, and 165 individual sonar surveys. Quality control checks on the bathymetric surveys are complete and the data are being processed. Processing of this data set will occur during FY 2023 with reporting on this data set occurring in the next work plan.

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.

In April 2022, the following contributions were made to the control network through the river mile (RM) 87-167 channel mapping effort:

- 218 pre-existing network stations were occupied,
- 64 topographic surveys were performed,
- 666 repetitious angle shots were added to the network,
- 401 benchmark/backsight pairs were used,
- 148 mechanical total stations were set up, measuring 452 repetitious shots,
- 179 robotic repetitious shots were acquired,
- 165 sonar projects were collected and georeferenced, and
- 113 temporary instrument stations were established.

The CRe control network now includes 2985 points, with 1806 positioned through least-squares adjustment of multiple measurements. The network results are consistent with alternate processing and adjustment methods (e.g., AUSPOS, OPUS Projects) within < 5 cm at 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) this fiscal year.

This migration requires new horizontal and vertical coordinates to be computed, which model tectonic plate rotations and will more accurately align with high-resolution satellite data. Intra-plate velocities will become integral to each position within the National Spatial Reference System and these changes will need to be considered within the context of long-term monitoring of the Colorado River ecosystem.

Element B.5. Streamflow and Fine Sediment Modeling

The purpose of Project Element B.5 is to develop models for predicting the concentration and transport of silt- and clay-size sediment. This project is proceeding in collaboration with personnel from Project A and input from scientists working on Projects E and G. Existing models in use by GCMRC and 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 and nutrient dynamics, which are increasingly recognized as potentially important controls on native and nonnative fish populations (Ward and others, 2016).

In FY 2022, we began 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 the extensive suspended sediment and water-quality data sets collected over the past two decades (Topping and others, 2021) to provide model inputs and for validation/calibration. Preliminary model results highlight the importance of eddy exchange in accurately capturing the timing and attenuation of fine sediment pulses as they travel downstream following tributary inputs. We also find that mud storage and release from bed/bar deposits is an important control on turbidity, particularly at relatively low levels of turbidity that are nonetheless important for controlling biological resources (e.g., native and nonnative fish) and as a driver of primary productivity. This effort will improve our ability to predict how dam operations, including high-flow experiments, affect concentrations and transport of all sizes of suspended sediment. This work leverages existing monitoring efforts to improve predictive modeling capabilities for fine sediment and will not lead to new or additional monitoring efforts.

This element was included in the FY 2021-23 TWP as unfunded in the event that other funding sources could be found to support the important modeling objectives. Other funding sources were found in FY 2022 from the USGS Ecosystems Mission Area. These funds were supplemented with unspent TWP funds.

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Durning, L.E., Sankey, J.B., Yackulic, C.B., Grams, P.E., Butterfield, B.J. and Sankey, T.T., 2021, Hydrologic and geomorphic effects on riparian plant species occurrence and encroachment—Remote sensing of 360 km of the Colorado River in Grand Canyon: Ecohydrology, v. 14, no. 8, e2344, https://doi.org/10.1002/eco.2344.

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Grams, P.E., Buscombe, D., Topping, D.J., Kaplinski, M.A., and Hazel, J.E., Jr., 2019, How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise. Earth Surface Processes and Landforms, v. 44, no. 1, p. 160-178, https://doi.org/10.1002/esp.4489.

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Project B Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$382,144	$5,000	$32,000	$353,293	$0	$62,262	**$834,699**
Actual Spent	$436,289	$7,555	$48,891	$8,000	$0	$60,974	**$561,709**
(Over)/Under Budget	**($54,145)**	**($2,555)**	**($16,891)**	**$345,293**	**$0**	**$1,288**	**$272,990**
FY21 Unspent Funds	**$0**					FY22 Unspent Funds	**$272,990**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent; etc.)*

FY22 Comments:
-Overspent Salaries is due to bringing staff from other USGS centers and overtime associated with the Channel Mapping river trip that was rescheduled from FY21.
-Overspent Travel & Training is due to field work and the Channel Mapping river trip that was moved from FY21 to FY22 due to Covid-19.
-Overspent Operating Expenses is due to necessary Inertial Navigation System equipment rental for the Channel Mapping river trip.
-Underspent funds in Cooperative Agreements is due to personnel working on this project left Northern Arizona University and the agreement will not be continued. The work will be accomplished by increasing staff at GCMRC.

Project B Deliverables: Sandbar and Sediment Storage Monitoring and Research

Presentations:

Mueller, E.R., and Grams P.E., 2021, A morphodynamic model to evaluate long-term sandbar rebuilding using controlled floods: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, October 2021.

Grams, P.E., 2022, The effects of high-flow experiments and dam releases on sandbar erosion and deposition in Marble and Grand canyons: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.

Grams, P.E., 2022, Sediment dynamics in western Grand Canyon during 2021 Spring disturbance flow: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.

Grams, P.E., 2022, Summary of sediment and sandbar projects—GCMRC Projects A and B, LTEMP Goal 7: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022.

Grams, P.E. and Mueller, E.R., 2022, Predicted effects of alternative summer 2022 release scenarios on sediment and sandbars: Glen Canyon Dam Adaptive Management Program Webinar on Glen Canyon Dam Summer 2022 Release Pattern, March 2022.

Grams, P.E., 2022, Multi-decadal sandbar response to flow management downstream from a large dam—The Colorado River in Marble and Grand canyons, Arizona: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, August 2022.

USGS Reports:

Hazel, J.E., Kaplinski, M.A., Hamill, D., Buscombe, D., Mueller, E.R., Ross, R.P., Kohl, K., and Grams, P.E., 2022, Multi-decadal sandbar response to flow management downstream from a large dam—The Glen Canyon Dam on the Colorado River in Marble and Grand Canyons, Arizona: U.S. Geological Survey Professional Paper 1873, prepared in cooperation with Northern Arizona University, 104 p., https://doi.org/10.3133/pp1873.

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USGS Data Releases:

Kaplinski, M., Hazel, J.E. Jr, Grams, P.E., Gushue, T., Buscombe, D.D., and Kohl, K., 2022, Channel mapping Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona - Data: U.S. Geological Survey data release, https://doi.org/10.5066/P98GFP93.

Web Applications:

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

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

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

Project C: Riparian Vegetation Monitoring and Research

Project Lead	Emily Palmquist	**Principal Investigator(s)** (PI)	Emily Palmquist, USGS, GCMRC Brad Butterfield, NAU
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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) 2022. Products completed during this time frame are included in the "Deliverables" section. Results of both completed and on-going work initiated in FY 2022 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 additional randomly selected sandbars, debris fans, and channel margins in August-October 2022. Between river miles (RM) -15.5 and 240, 94 randomly selected sites, and 45 annually sampled long-term sites were sampled. Data from 2022 are currently being entered into the riparian vegetation database and error checked.

Trends in native and nonnative species richness, cover by functional groups and species, and frequency of species are reported on a 5-year basis as a separate, stand-alone report, in order to thoroughly address methods, interannual variation, uncertainties, management implications, and interpretations of trends.

A summary of the overall status and trends in riparian vegetation composition and cover from 2014 through 2019 was drafted as a USGS Status and Trends Open-File Report and is currently in press. Specific metrics to be reported annually are currently being determined as part of a larger, ongoing metrics development project (U.S. Department of the Interior, 2020; FY2021-23 TWP, Reclamation section C.12). The metrics under consideration are total plant cover, native plant richness, and native to nonnative species cover ratio, which are all metrics that can be derived from the riparian monitoring program and repeat aerial imagery analysis.

Presence and cover data for a preliminary set of eight plant species were analyzed with environmental and biotic variables using monitoring data from 2016 through 2020. An ordinal, zero-augmented Bayesian model was developed to simultaneously model presence versus cover responses with respect to temperature, hydrology, substrate, site conditions, and their interactions with mean annual temperature.

These preliminary analyses indicate that 1) presence and cover can differ in their controlling environmental variables and direction of responses, 2) the timing of daily load-following flows plays a significant role in riparian plant presence and cover, with coyote willow (*Salix exigua*) exhibiting reductions in both presence and cover where daily tides are high in the afternoon, and 3) higher air temperature changes how plants respond to environmental variables, including hydrology. These analyses are ongoing, and the model is being used for analyzing data for an additional 32 species.

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

We completed analysis of plant responses to the 2021 spring disturbance flows (see Project O for further details) that provided unique insights into how riparian plants with different habitat preferences and functional strategies respond to short-term flow anomalies.

Specifically, we quantified how multiple metrics of plant water status in tall fescue (*Schedonorus arundinaceus*), a hydric grass that grows in near-channel habitats that are inundated and exposed by daily fluctuating flows, and arrowweed (*Pluchea sericea*), a mesic shrub that thrives in the zone inundated by HFEs, responded to the low and high flow phases of the spring disturbance flows, interpreted in the contexts of both drought and inundation stress.

Among other results, we found unique responses of the two species to low versus high flow anomalies (Figure 1), where *Schedonorus* exhibited stem cavitation risk (drought-induced embolism) in response to low flow conditions, while *Pluchea* tolerated low flow conditions by reducing leaf water content and capitalizing on high flow conditions exhibited by increased stem water potential. These asymmetric responses to low and high flows provide insights into how plants with different habitat preferences and functional strategies respond to flow variation and provide predictions about how these and similar species would likely respond to longer duration changes to the hydrograph. A manuscript is in review (Butterfield and others, in review).

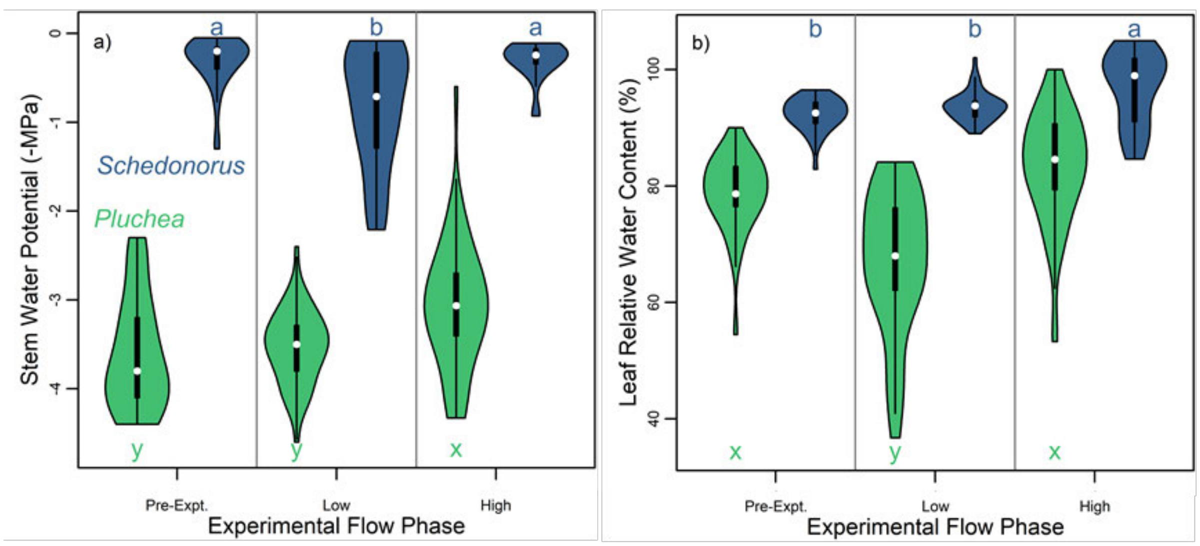

Figure 1. Physiological responses to the spring disturbance flows. *Schedonorus* stem water potential decreased during the low flow phase, while that of *Pluchea* increased during the high flow phase, relative to the pre-experiment conditions. Conversely, leaf relative water content of *Schedonorus* increased during the high flow phase, while that of *Pluchea* decreased during the low flow phase. These different responses reflect plant adaptations to variation in drought stress and inundation that can help inform predictions of plant responses to HFEs and other types of flow anomalies.

We also conducted a greenhouse experiment to determine how well species' local hydrological niches – specifically the elevations above the CRe channel at which they generally occur – correspond with their drought or inundation tolerances. We anticipated that the results could tell us the extent to which the current vegetation has been structured by high flow anomalies (inundation tolerances) versus low flow anomalies (drought tolerances). We implemented drought, control, and flooding treatments and measured stomatal conductance and new root growth as indicators of stress responses.

Among other results, we found (1) a strong relationship between species hydrological niche (elevation above the channel in the CRe and inhibition of root growth under flood conditions (Figure 2) and (2) increasingly divergent stomatal conductance responses to drought with increasing elevation above the channel (not shown).

These results suggest that current species distributions along hydrological gradients in the CRe have been structured by the amplitude of high flow anomalies (HFEs and peak load following flows) and are likely to be particularly sensitive to future inundating events, but also that the magnitude and duration of low flow anomalies are likely to differentially affect species in predictable ways based upon their physiological and growth responses to our experimental treatments. These results are included in a manuscript nearing submission for peer review and will be presented at the Annual Reporting Meeting in January 2023.

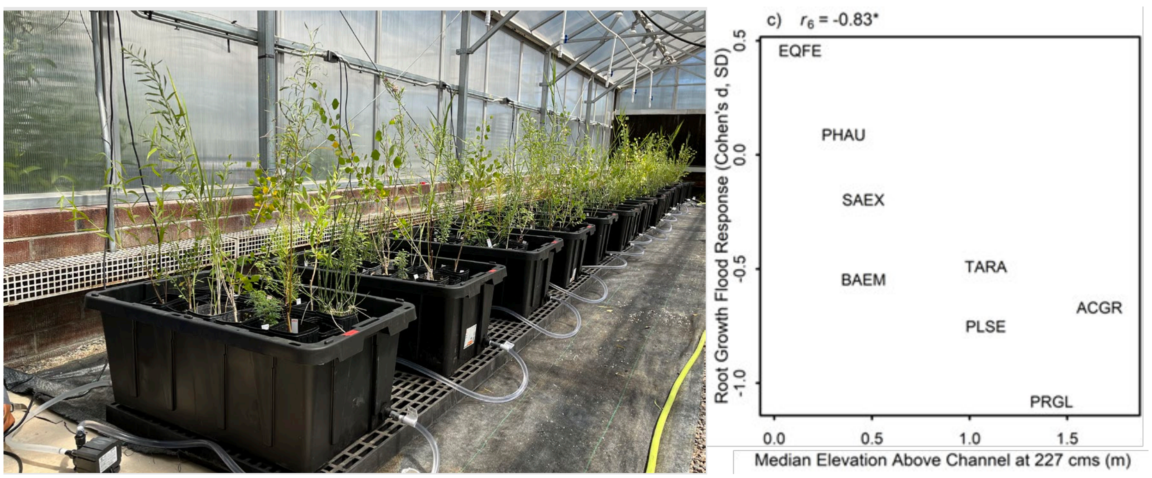

Figure 2. Experimental setup and selected results from the greenhouse experiment. Experimental treatments were established at the Northern Arizona University (NAU) Research Greenhouse Complex, where bins with recirculating pumps were assigned to one of three water treatments: drought, control or flood. On the right is one selected result, demonstrating that plants that naturally grow at higher elevations above the channel in the CRe experience greater root growth inhibition when subjected to flooding in the greenhouse. Species are: EQFE – *Equisetum x ferrissii*, PHAU – *Phragmite australis*, SAEX – *Salix exigua*, BAEM – *Baccharis emoryi*, TARA – *Tamarix ramossisima* x *chinensis*, PLSE – *Pluchea sericea*, PRGL – *Prosopis glandulosa*, ACGR – *Acacia greggii*.

Element C.3. Predictive Models and Synthesis

Science Questions

- What are the predicted changes to 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

We published a peer-reviewed manuscript (Butterfield, Palmquist and Yackulic, 2022) on the effects of streamflow seasonality on the composition and diversity of riparian vegetation within the CRe. Specifically, we developed empirical models of plant species habitat requirements with respect to their suitable hydroclimate – the temperature, precipitation, and vapor pressure deficit during the lowest and highest streamflow months – and projected those models under different simulated seasonal timings of low and high streamflow months in the CRe. This study leveraged extensive open-source data, including millions of plant occurrence records from across the US, climate data, and a novel application of the National Hydrography Database.

Among other results, we found that (1) total species richness is predicted to be highest with summer high flows, (2) native-to-nonnative ratio is predicted to be highest with winter low flows, and (3) species that have increased in cover over recent decades, such as arrowweed and seepwillows (*Baccharis* sp.) exhibit particularly high habitat suitability when high flows correspond with high temperatures (summer). Along with other results, this study demonstrates that the current composition of CRe riparian vegetation has been shaped by the seasonal timing of low and high flows out of Glen Canyon Dam and provides predictions for how that vegetation could change with seasonal alterations to the hydrograph.

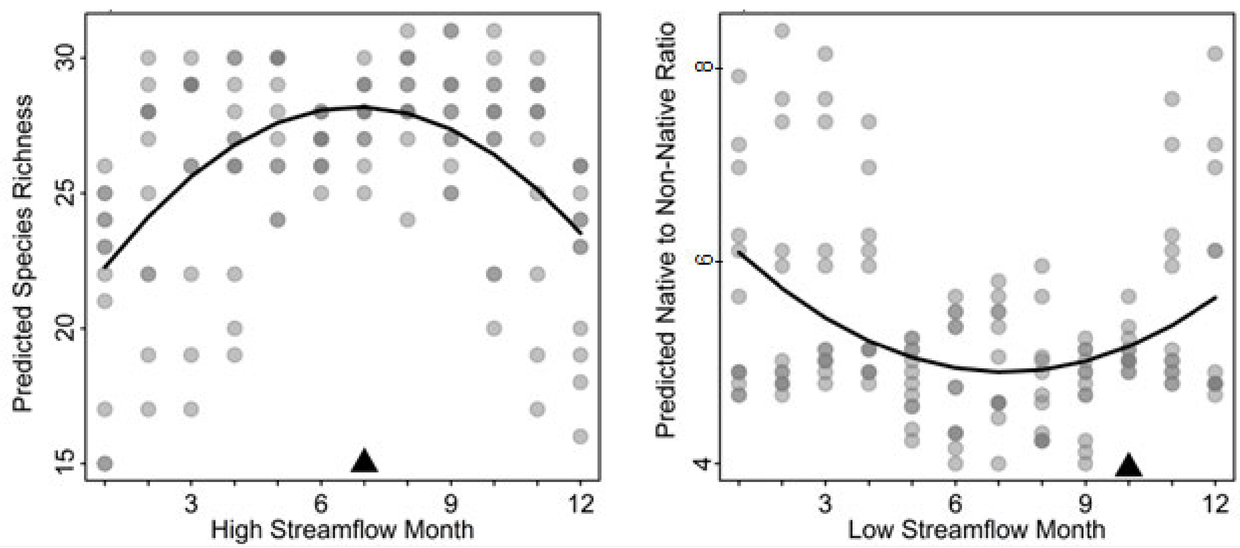

Figure 3. Selected results from the "hydroclimate" study published in Butterfield and others (2022). The panel on the left demonstrates the increase in predicted species richness with summer high streamflows, while the the panel on the right demonstrates the increase in native dominance with winter low streamflows. The triangles represent the months of high and low streamflow of the current hydrograph.

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 years past, we participated in planning meetings for NPS-led non-flow experimental vegetation treatments (U.S. Department of the Interior, 2020; FY 2021-23 TWP, Reclamation sections C.7 and C.8) to consult on ongoing and new work sites. Five campsites and a Glen Canyon National Recreation Area 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: -6.6 RM, Basalt Camp, Upper Clear Creek Camp, Granite Camp, 122 Mile Camp, and 202 Mile Camp. A manuscript describing the manipulative greenhouse experiment testing the influence of inundation on arrowweed was published in (Palmquist and others, 2022). This work indicated that individuals from different locations in the CRe have different phenotypes, that plant growth was strongly decreased with inundation, and that arrowweed responds to the environment in unique ways when compared to riparian trees. The information gained from this study can help understand arrowweed growth and expansion in the CRe, a key species in campsite encroachment and vegetation removals.

Additionally, we participated in the USGS/Tuba City Partnership Summer Camp for native youth by teaching students about riparian ecosystems at Lees Ferry and upstream. Topics covered included identifying plants, appropriate scientific collection of plants, plant physiology, and riparian restoration. The NPS/Grand Canyon Wildlands cooperative restoration project at Paria Beach was used as an illustration of restoration concepts, and a representative from Grand Canyon Wildlands also participated.

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Butterfield, B.J. and Palmquist, E.C., *in review*, Divergent physiological responses of hydric and mesic riparian plant species to a Colorado River experimental flow: Plant Ecology.

Butterfield, B.J., Palmquist, E.C., and Yackulic, C.B., 2022, The hydroclimate niche—A tool for predicting and managing riparian plant community responses to streamflow seasonality: River Research and Applications, v. 39, no. 1, p. 84-94, https://doi.org/10.1002/rra.4067.

Palmquist, E.C., Ogle, K., Whitham, T.G., Allan, G.J., Shafroth, P.B., and Butterfield, B.J., 2022, Provenance, genotype, and flooding influence growth and resource acquisition characteristics in a clonal, riparian shrub: American Journal of Botany, online, https://doi.org/10.1002/ajb2.16115.

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 C Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$134,307	$3,940	$1,565	$107,337	$0	$20,453	**$267,602**
Actual Spent	$133,693	$2,129	$1,102	$109,097	$0	$20,150	**$266,170**
(Over)/Under Budget	**$614**	**$1,811**	**$464**	**($1,760)**	**$0**	**$303**	**$1,432**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$1,432**
COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent; etc.)*							
FY22 Comments: -Underspent Salaries is due to technician turnover on this project. -Underspent Travel & Training were to compensate for increased botanist costs. A local conference was attended instead of a national conference. -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.J. and Palmquist, E.C., 2022, Riparian vegetation monitoring and modeling—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 12, 2022.

Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B.J., Dibble, K., Bair, L., and Tusso, R., 2022, Disturbance Flow Panel Session—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 12, 2022.

Pilkington, L., Stevens, L., Burke, K., Butterfield, B.J., Palmquist, E., and Sankey, J., 2022, Riparian vegetation science & management—webinar presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 9-10, 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/amwg.html.

Palmquist, E., Ogle, K., Butterfield, B.J., Whitham, T., Shafroth, P., and Allan, G., 2022, Provenance of a riparian shrub changes traits but not flood response under a common climatic setting: River's Edge West 20th Anniversary Riparian Restoration Conference, February 23-25, 2022, Grand Junction, CO.

Palmquist, E.C., 2022, Goal 11: Riparian Vegetation Draft Metrics—presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, April 13, 2022.
Palmquist, E.C., Ogle, K., and Butterfield, B.J., 2022, Riparian plant presence and abundance are differentially controlled by hydrology and temperature along a regulated, dryland river—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau and Southwest Region, September 12-15, 2022, Flagstaff, AZ.
Butterfield, B.J., Palmquist, E.C., and Yackulic, C.B., 2022, The hydroclimatic niche—A tool for predicting and managing riparian plant community responses to streamflow seasonality—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, September 12-15, 2022, Flagstaff, AZ.

Journal Articles:

Butterfield, B.J., Palmquist, E.C., and Yackulic, C.B., 2022, The hydroclimate niche—A tool for predicting and managing riparian plant community responses to streamflow seasonality: River Research and Applications, v. 39, no. 1, p. 84-94, https://doi.org/10.1002/rra.4067.
Samuels-Crow, K., Ogle, K., and Palmquist, E.C., 2022, What drought means for southwestern landscapes: Boatman's Quarterly Review, v. 35, no. 1, p. 16-19. (Article not available online)

USGS Data Releases:

Palmquist, E.C., Ralston, B.E., Sarr, D., Merritt, D.M., Shafroth, P.B., Scott, J.A., 2017, Southwestern riparian plant trait matrix, Colorado River, Grand Canyon, Arizona (ver. 2.0, January 2022): U.S. Geological Survey data release, https://doi.org/10.5066/P974VCDK.
Palmquist, E.C., Butterfield, B.J., and Ralston, B.E., 2022, Riparian vegetation data downstream of Glen Canyon Dam in Glen Canyon National Recreation Area and Grand Canyon National Park, AZ, from 2014 to 2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9KEHY2S.

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		
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Goals and Objectives

The LTEMP goal for Archaeological and Cultural Resourcesaintain 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: i) dam operations, ii) vegetation management, and iii) natural processes. While the dam and its operation are not the only sources of change affecting the CRe and associated archaeological sites, this project focuses on studying and monitoring dam effects, 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 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 2022 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 three elements (D.1, D.2, and D.3) that were funded in FY 2022.

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

Figure 1 summarizes methods and site class definitions for the aeolian classification system, and Figure 2 summarizes the results of using that system to monitor long-term changes at archaeological sites. Figure 2 shows that river-sourced aeolian sand supply has decreased since 1973 for nearly all archaeological sites, making most sites more erosion-prone. Specifically, the number of archaeological sites classified as Type 1 because they have the highest likelihood to receive wind-blown sand supply from fluvial sandbars, decreased over each monitored time step, from 98 in 1973 to only four in 2021–22 (Figure 2). In 2021–22 there are an additional seven Type 1VR sites that have maintained the Type 1 site characteristics owing to site-specific vegetation management efforts implemented between 2019 and 2022 by the National Park Service (Pilkington and others., 2022); without the vegetation management work these seven sites would likely be classified as Type 2 or 3.

Most of the sites that were Type 1 in 1973 transitioned over time to Type 2 or 3 sites, primarily due to the expansion of riparian vegetation onto subaerial sandbars throughout the river ecosystem. Riparian vegetation can either create a barrier to aeolian sand transport from sandbars to archaeological sites in the case of Type 2a and Type 2c sites, or it can completely cover the subaerial sandbar deposit such that there is no longer a source area for aeolian sand supply thus resulting in a site being classified as Type 3 (East and others, 2016). Thus, many sites that were classified prior to 2021–22 as one of the three subcategories of Type 2 sites owing to the presence of a riparian and/or topographic barrier to aeolian sand transport, later transitioned to Type 3 sites owing to continued vegetation expansion (Figure 2). The number of sites classified as Type 3 increased from 27 in 1973 to 148 in 2021–22 primarily due to these vegetation expansion processes. The sites classified as Type 2AVR (3), 2bVR (3), and 2cVR (2) in 2021–22 would instead currently have the characteristics of Type 3 sites if not for site-specific vegetation management efforts implemented between 2019 and 2022 by the National Park Service (Pilkington and others, 2022).

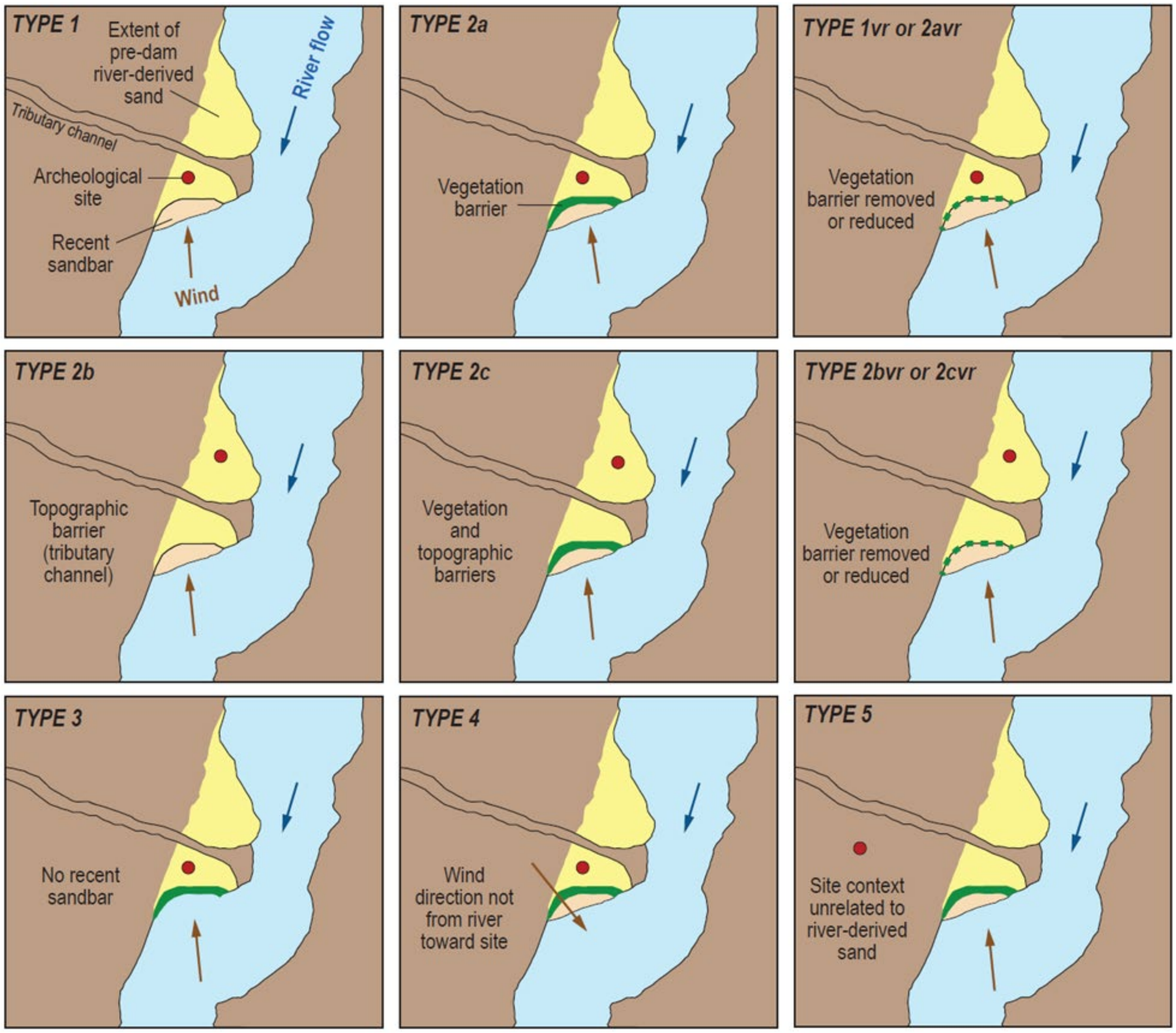

Figure 1. Overview of the aeolian classification system and site class definitions (adapted from East and others, 2016; 2017).

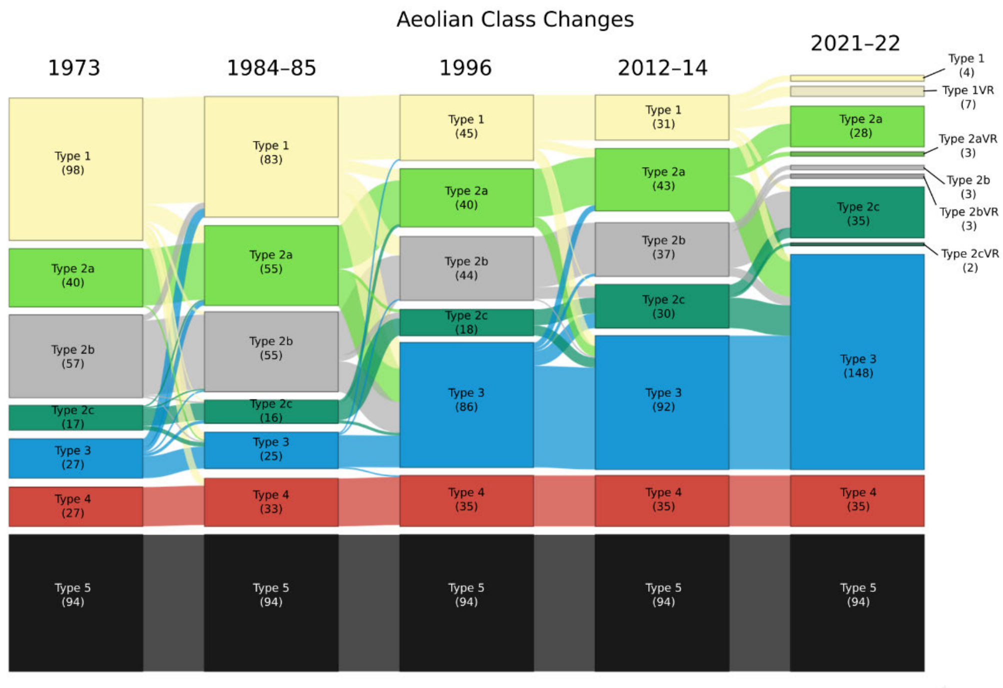

Figure 2. Diagram of aeolian class changes over time for 362 archaeological sites in the Colorado River corridor, Grand Canyon National Park. See Figure 1 for definition of site class types (preliminary results, do not cite).

Figure 3 summarizes methods and site class definitions for the drainage classification system, and Figure 4 summarizes the results of using that system to monitor long-term changes at archaeological sites. Figure 4 shows that the proportion of sites eroding by gully processes has increased since 2000. Specifically, the proportion of sites without drainages (e.g., gullies or arroyos) has decreased from 2000 to 2021–22 and the proportion of sites with drainages has increased during that time, indicating an overall increase in sites affected by gullying processes (Figure 4). For example, from 2016–17 to 2021–22, sixteen Type D1 sites developed drainages. A small number of sites transitioned from having terrace (Type D2) or river-based (Type D4) drainages in 2000 to not having drainages in 2016–17 owing to fluvial or aeolian sediment backfilling of the drainages (gully annealing, *sensu* Sankey and Draut, 2014). However, the majority of changes in site classifications indicate the progressive development of new drainages and the downcutting of existing drainages to lower base levels (e.g., terrace to side-canyon or river), indicating increasing erosion and greater future erosion potential for the archaeological sites. As of 2021–22, 41 sites have side-canyon based drainages and 98 have river-based drainages (Figure 4); these sites are effectively at the evolutionary endpoint of drainage development because they are graded to the lowest possible base level for their respective locations. In 2021–22, 117 sites do not have drainages (Figure 2) and these sites may or may not be vulnerable to the development of new drainages in the future, depending on the specific geomorphic setting. However, 106 sites in 2021–22 have terrace-based drainages that could downcut and become integrated with the base-level of the river in the future; Type D2 sites represent the intermediary stage of drainage development in the system.

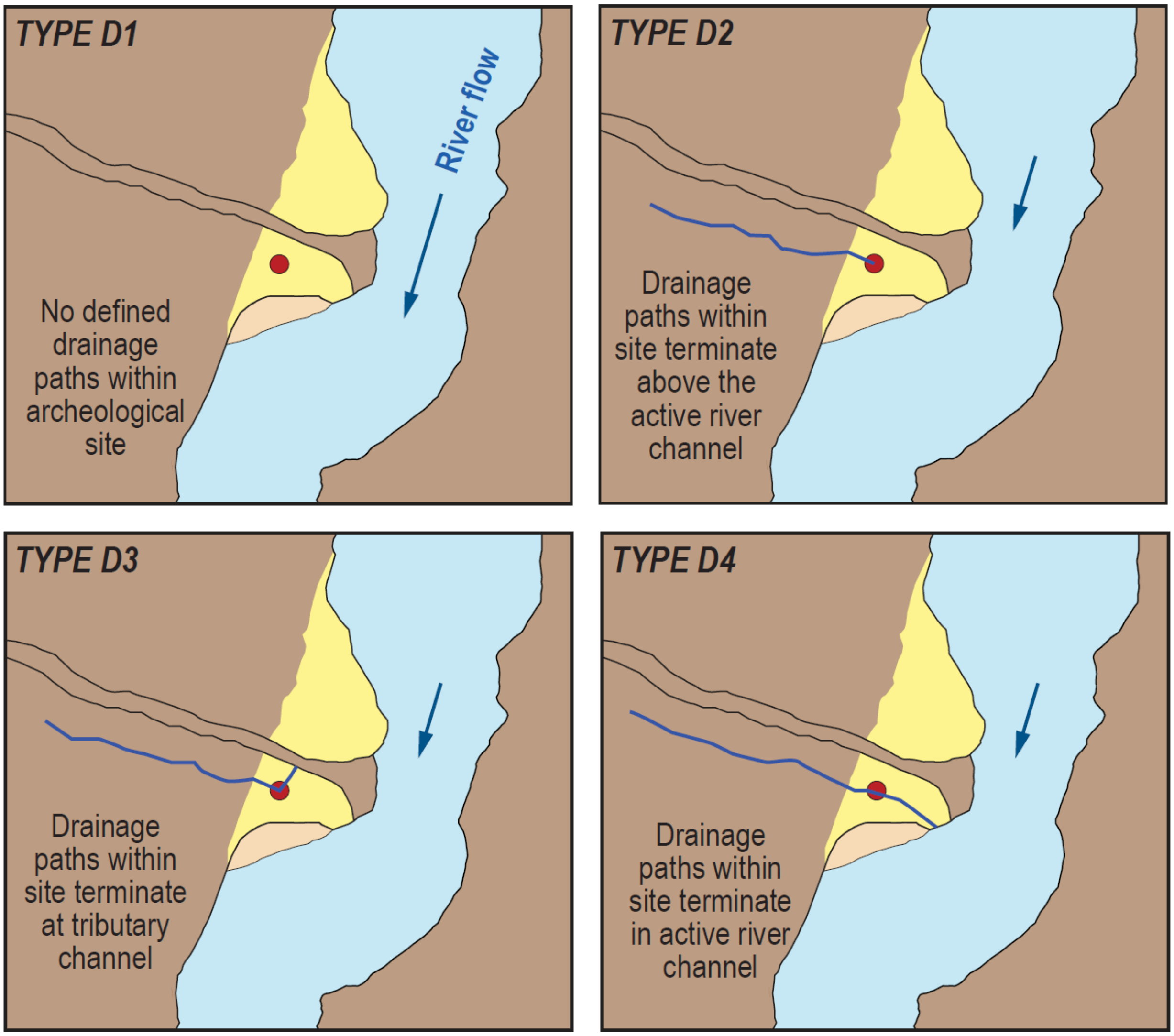

Figure 3. Overview of the drainage classification system and site class definitions (adapted from East and others, 2016; 2017).

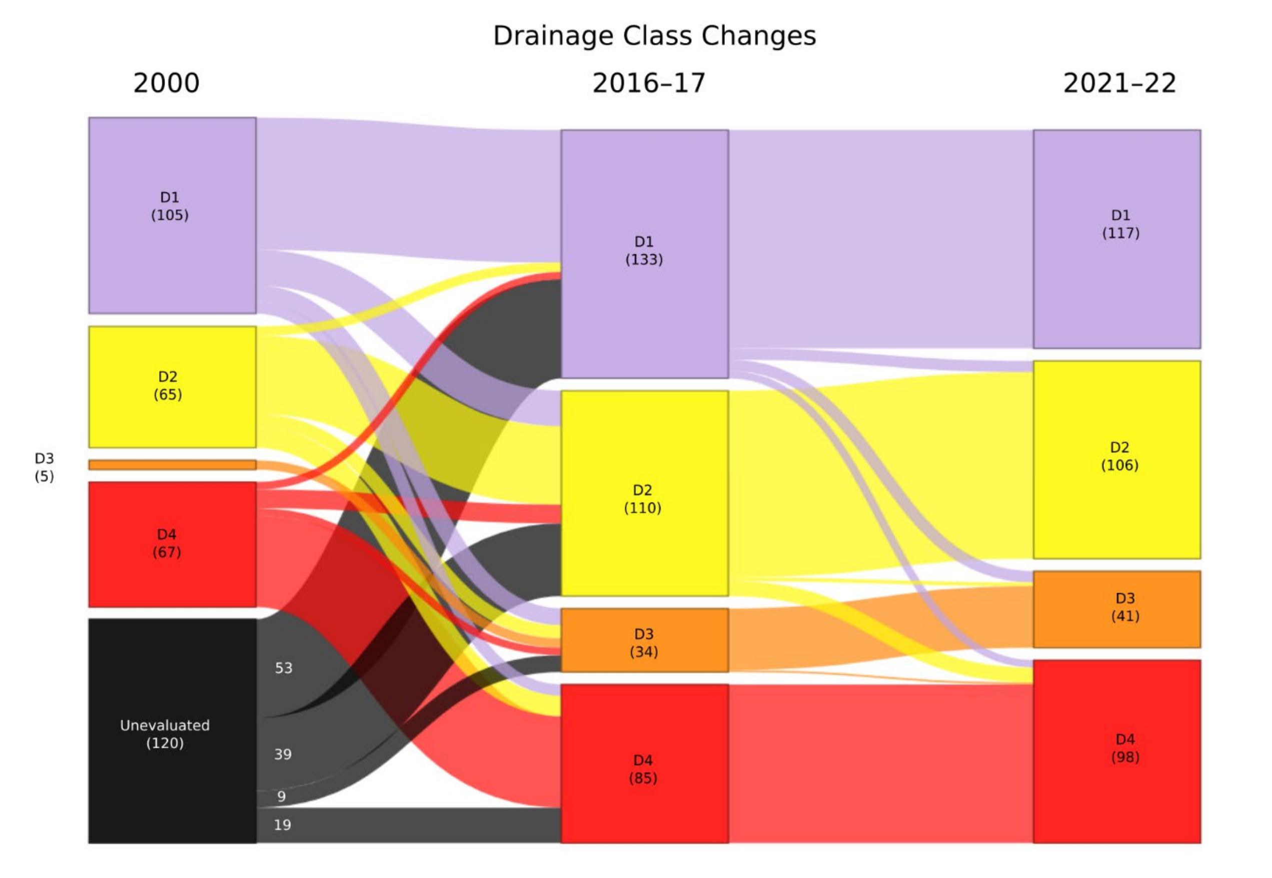

Figure 4. Diagram of drainage class changes, based on field assessments of archaeological sites' geomorphic context in 2000, 2016–17, and 2021–22. See Figure 3 for definition of site class types (preliminary results, please do not cite).

Figure 5 summarizes results of topographic changes at a sample of the population of archaeological sites, determined with lidar remote sensing for the decade from 2010 to 2020 (Caster and others, 2022). Sites that underwent net erosion during this time frame occur in each of the observed combinations of site classifications. Specifically, one of the five Type 1 sites, two of the four Type 2 sites, and two of the three Type 3 sites monitored with lidar underwent significant erosion, as did the one Type 4 site that was monitored. Previous work with topographic change detection from lidar remote sensing has shown that many sites have eroded at times during the decade, but that those sites that have aggraded have tended to be located adjacent to and downwind of river sandbars that are periodically resupplied with sand by HFEs and which, in turn, provide a consistent source of wind-blown river sediment supply to downwind archaeological sites (Collins and others, 2016; East and others, 2016; Sankey and others, 2018b).

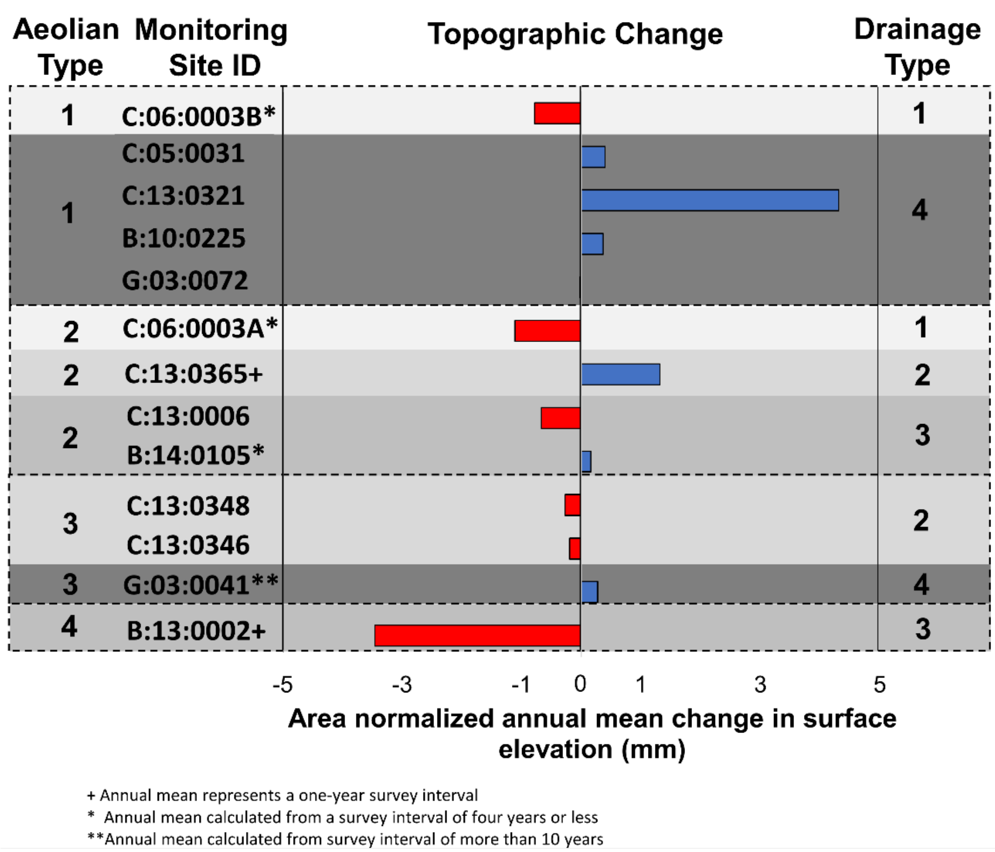

Figure 5. Topographic changes for select sites by classification (Caster and others, 2022).

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 2022, 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, a retired USGS riparian ecologist, and Mr. Alan Fairley, an experienced amateur photographer.

In 2022, we matched a total of 80 historical photographs. As in 2021, we focused primarily on matching color slide images of campsites originally photographed in 1973 (n=72) as part of the NPS-sponsored Borden-Weeden campsite carrying capacity study (Borden and others, 1975; Weeden and others, 1975). In addition, we matched a few photographs taken by E.C. La Rue in 1923 (n=3) and by Robert Brewster Stanton in 1889-1890 (n=5).

As noted in the 2021 Annual Report, the 1973 images are particularly useful to match as 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 already becoming evident but before substantial transformation of the riparian zone had occurred (Figure 6). Many of the campsites available 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 (Figure 6a-b); however, many other camps are no longer usable today due to significant vegetation encroachment and sediment loss (Figure 6c-d). Regardless of whether camps remain habitable or not, vegetation encroachment and the reduction of open sand areas is a common theme in all the 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 the 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). In 2022, we conducted some preliminary exploratory analysis of the vegetation data to examine the distribution of species occurrence by inundation zone, along with changes in the composition of riparian plant communities within each zone (Figure 7).

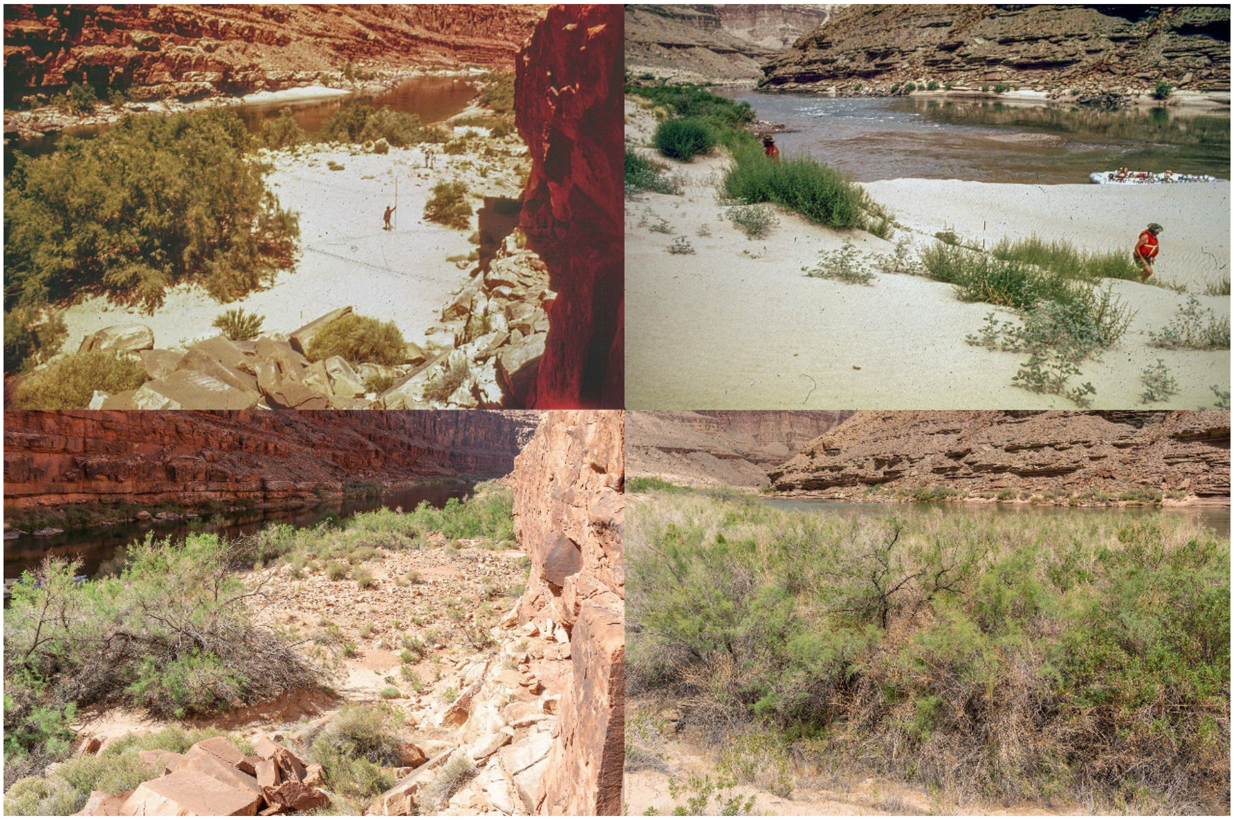

Figure 6. Two examples of campsites photographed by Borden-Weeden in July 1973 (top images, 6a left, 6c right) compared to their current condition (bottom images, 6b left, 6d right) in May 2022. Left photo match (6a-b) taken at RM 20.0, left bank, looking upstream. This place is still used as a campsite today, despite significant loss of open sand area from wind deflation, debris flows, vegetation growth, and runoff erosion. Right photo match (6c-d) at RM 122.4., left bank, looking across the river. 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; 2022 photographs (bottom images) by A.H. Fairley, (6bt) April 29, 2022, and (6d) May 6, 2022.

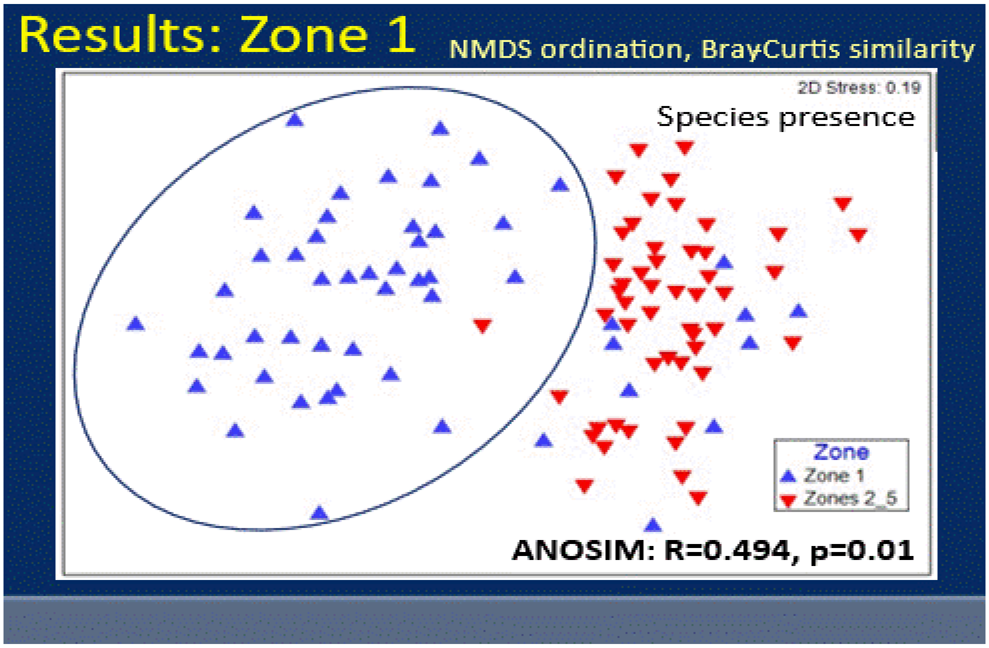

Figure 7. Ordination of recorded species by riparian zone. Note the distinctive vegetation assemblage growing in Zone 1, immediately adjacent to the river, compared to the species found in Zones 2-5 (farther from the river). Preliminary data, please do not cite.

Element D.3. Cultural Program History

Science Questions/Hypotheses Addressed

- How have the previous three decades of research and monitoring informed current preservation strategies and NHPA compliance activities in the CRe?
- How have multi-cultural perspectives informed development of the cultural program of the GCDAMP since its inception 25 years ago?

Results

In FY 2022, we continued to make progress on compiling a history of the GCDAMP cultural program. This year we were fortunate to have the assistance of a Native American student from Northern Arizona University (NAU), Brooke Damon, who served as an intern with GCMRC for ten weeks during the summer. Due to the small amount of funding budgeted for this element and because of continuing restrictions imposed by the Covid-19 pandemic, the FY 2022 effort focused exclusively on archival research conducted online. A comprehensive bibliography of relevant cultural and Tribal presentations and reports from the past 25 years of AMWG meetings was compiled as part of this ongoing effort in FY 2022. We are grateful to the Institute for Tribal Environmental Professionals for providing financial support for the student intern.

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Project D Budget

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$214,084	$10,600	$2,806	$0	$0	$28,040	**$255,530**
Actual Spent	$208,980	$4,351	$14,417	$0	$0	$28,072	**$255,820**
(Over)/Under Budget	**$5,104**	**$6,249**	**($11,611)**	**$0**	**$0**	**($32)**	**($290)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($290)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to staff turnover at the end of the FY.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent amount in Operating Expenses was to cover required instrument calibration.

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

Presentations:

Fairley, H.C., Scott, M., and Fairley, A.H., 2022, Assessing 50 years of change in riparian condition along the Colorado River in Grand Canyon, Arizona—presentation: 16th Biennial Conference on Science and Management, Flagstaff, AZ, September 15, 2022.

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Papers and Reports:

Caster, J., Sankey, J.B., Fairley, H., and Kasprak, A., 2022, Terrestrial lidar monitoring of the effects of Glen Canyon Dam operations on the geomorphic condition of archaeological sites in Grand Canyon National Park, 2010–2020: U.S. Geological Survey Open-File Report 2022–1097, 100 p., https://doi.org/10.3133/ofr20221097.

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

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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, fish are food limited (Cross and others, 2011) and energy (carbon) produced within the river is a preferred macroinvertebrate 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 approach this 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 Canyon and Marble Canyon, 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:** The relationship between Colorado River suspended silt-and-clay concentration and total P extends to the soluble reactive P (SRP) pool.
- **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 mainstem 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 and flannelmouth sucker have lower basal metabolic demands than related taxa.
- **H12:** This low metabolic demand means the ecosystem can sustain large populations of these species despite relatively low primary production and that these species can survive through relatively extended periods of low food availability.

Below we focus discussion on FY 2022 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). This includes ongoing 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 have been collected across FY 2021 and FY 2022 toward the construction of a Colorado River P budget (Table 1). 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, Figure 1). Remarkably, the same ln-ln relationship holds regardless of the tributary or mainstem location. Storm-triggered samples from both the Paria River "PRI" and the Little Colorado River "LCI" represent the upper end of both silt and clay and TP concentrations, whereas samples collected from tributaries "TRI" and from the mainstem Colorado River "MAIN" span nearly four orders of magnitude for TP (from 0.002 to 8 mg/L) and five orders of magnitude for silt and clay (from 0.2 to 20,100 mg/L silt & clay). Paired samples of dissolved P and silt and clay were limited during FY 2021, with 23 samples from the Paria River at base flow, 21 samples from storm-based Paria River, and 8 samples from storm-based Little Colorado River ISCO brand sampler collections.

These samples indicate no predictable relationship between silt and clay concentration and dissolved P across locations, but do suggest some relationships within storms. We plan to examine these relationships further with the additional dissolved P and silt and clay samples collected in 2022 (which are currently waiting to be analyzed at Flathead Lake Biological Station and in collaboration with Project A, respectively).

Table 1. A summary of P samples collected in FYs 2021 and 2022 from the Colorado River below Glen Canyon Dam and its tributaries. P samples collected from the Glen Canyon Dam draft tubes and Lees Ferry, as part of the Lake Powell Water-Quality Monitoring Program (Appendix A), will also be used for this effort. *Indicates that separate suspended-sediment samples were collected for silt and clay concentration as part of Project A.

Type	Sites/ Storms	TP	Dissolved P	Silt & Clay
Paria Base flow	1 (site)	27	27	0
Paria Storm (ISCO)	14 (storms)	109	79	*
Little Colorado River Storm (ISCO)	12 (storms)	76	13	*
Little Colorado River (Grab)	3 (sites)	26	26	26
Diamond Creek	1 (storm)	3	3	3
CS Mainstem	8 (sites)	129	0	13
CS Tributary	21 (tributaries)	53	0	51

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

In FY 2022, we focused effort on writing up riverine sediment P incubations that were conducted in FY 2021. We convened a four-day work group in Moab during early December to devise a conceptual diagram, conduct data analyses, and to outline a manuscript. The manuscript was submitted to a journal for consideration in early December (Deemer and others, submitted).

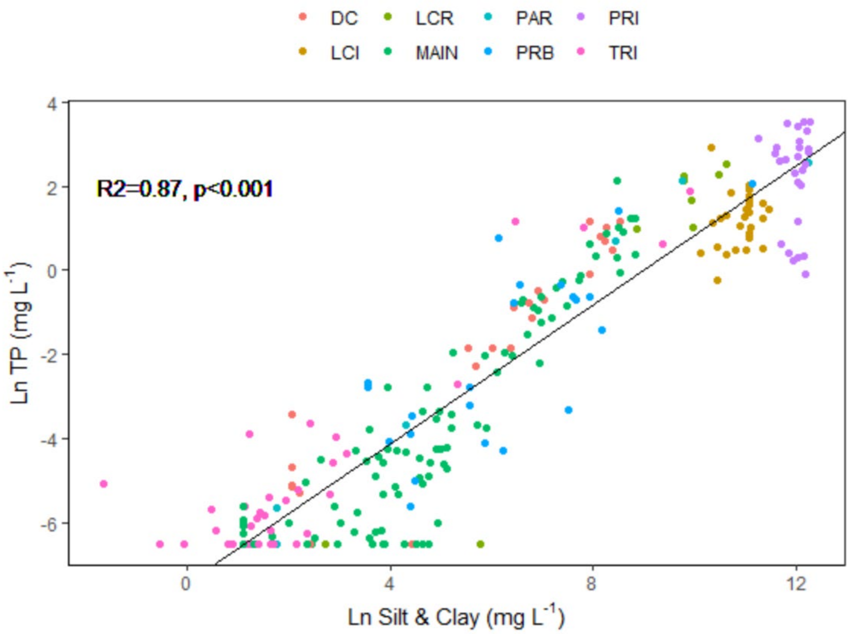

Figure 1. Positive natural log relationship between mainstem and tributary silt and clay concentration and TP concentration for samples collected in FY 2021 (n=155). Color indicates sample location and type ("DC"=Colorado River above Diamond Creek, "LCI"=Little Colorado River at Cameron ISCO, "LCR"=Little Colorado River grab sample, "MAIN"=mainstem Colorado River grab sample, "PAR"= Paria River grab sample, "PRB"=monthly USGS Paria River base flow grab sample, "PRI"=Paria River ISCO sample, and "TRI"= tributary grab sample (generally by community scientists).

These riverine sediment P incubations were conducted to examine the controls on riverine sediment P release. The incubation experiment was designed to quantify calcite content in sediments and to isolate the effects of redox state (low dissolved oxygen) and pH on sediment P release across three sites: Glen Canyon, Pearce Ferry, and the Paria River. Low dissolved oxygen concentrations can cause iron bound P release by increasing the solubility of the iron (Caraco and others, 1993), whereas low pH can lead to calcite bound P release by increasing the solubility of Ca^{2+} and HCO_3^- (Corman and others, 2016). Low pH conditions often co-occur with low dissolved oxygen conditions in natural environments due to heterotrophic respiration making these mechanisms for P release difficult to disentangle. The incubations successfully simulated a range of observed pH (6-8.8) and oxygen (0-9.4 mg L^{-1}) levels. Values of pH were chosen to represent the minimum and maximum pH observed at Lees Ferry since dam closure, and oxygen concentrations represent a slightly larger range of conditions than are observed in the Colorado River (minimum dissolved oxygen of 2.5 mg L-1 observed in Glen Canyon in September of 2022 (see Appendix 1).

We find support for pH-mediated P release from calcite across all three sites. The magnitude of P release and total protein production was lower in bottles filled with tailwater sediment than in bottles with sediment from downriver sites. At the downriver sites, lower pH treatments resulted in declining water column dissolved inorganic phosphorus: soluble reactive phosphorus (DIN:SRP) ratios, which dropped below the Redfield ratio of 16:1, increasing water column total protein production, and down-regulating alkaline phosphatase production.

We estimate that a decline in river pH from 8 to 7 would stimulate downstream sediment P release on the same magnitude as SRP loading from the dam outflow. We expect such a decline in pH could result from either storm inputs or from shifting the height of dam releases; however, downstream pH data are rather limited and the maximum recorded diel range in pH is 0.25 units (from 7.93 to 8.18 at the U.S. Geological Survey gage site 09383100 Colorado River above Little Colorado River near Desert View, AZ; U.S. Geological Survey, 2022; Reibold and others, in prep). This additional P supply could be enough to stimulate 1.8 kg d^{-1} per river kilometer of additional aquatic insect production if downstream P limitation is similar to that in Glen Canyon (Yard and others, 2023).

We are currently planning to conduct incubations to quantify equilibrium P concentrations in Colorado River sediments in FY 2023.

Element E.2.

GPP Modeling Progress

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, γ, that helps predicts weekly-scale gpp, especially when combined with information about discharge and flow regime (hydropeaking or steady; Deemer and others, 2022). A proxy for bed grain size is needed because reach-scale bed grain size is not measured as a regular component of the Project B monitoring programs (and would be extremely expensive to achieve). Briefly, γ is calculated based on the relationship between discharge and turbidity at a given site. Lower values of γ indicate a coarser bed grain size distribution (with less turbidity resulting from a set discharge), whereas higher values of γ indicate a finer bed grain size distribution (with more turbidity resulting from a set discharge). Our model showed higher gpp when γ was low (Deemer and others, 2022), consistent with the hypothesis that silt and clay concentrations negatively affect instantaneous gpp via reductions in light availability.

Contribution of Diatoms versus Macrophytes to GPP

At Lees Ferry, gpp is not correlated with P concentrations, but chlorophyll *a* is modestly correlated with P concentrations. This may be because macrophytes contribute a large fraction of gpp, but have access to sediment P stores that the more palatable diatom community does not. 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 2021, a pilot study was conducted primarily to refine the methodology used to address this hypothesis (see FY 2021 Annual Report, USGS Grand Canyon Monitoring and Research Center, 2021). This project has since been discontinued because of lack of capacity (and additional priorities being identified).

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 Trout Recruitment and Growth Dynamics (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 site-specific macrophyte cover and *Potamogeton* density to brown trout site specific catch data. Image labeling (image-based classification training data collection) was conducted in 2022 using MakeSense.ai software, and additional labels will be generated in 2023. Models are currently in development, and we plan to share results in 2023.

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. Briefly, we compared the discharge at the USGS gages Paria River at Lees Ferry, AZ, 09382000, and the Colorado River at Lees Ferry, AZ, 09380000 (U.S. Geological Survey, 2022), to setup incubations using the flood samples and Colorado River water from Lees Ferry (ratios of 1:10.3 and 1:20.2, respectively; Figure 2A). A total of fifteen bottles were set up for each time point and bottles were destructively sampled in triplicate immediately after bottle set up, and 1, 3, 5 and 7 days later. Bottles were incubated uncapped in the dark between 10- and 13-degrees C. Before amending Colorado River water with Paria River storm samples, river water concentrations of TDP and SRP were undetectable (< 1.5 and < 0.8 µg L-1 P, respectively) and TP measured 3.1 ug L-1 (Figure 2B). Storm sample amendments increased water column P by nearly two orders of magnitude (206 µg L-1 TP, 63.9 µg L-1 TDP, and 2.9 µg L-1 SRP). 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.

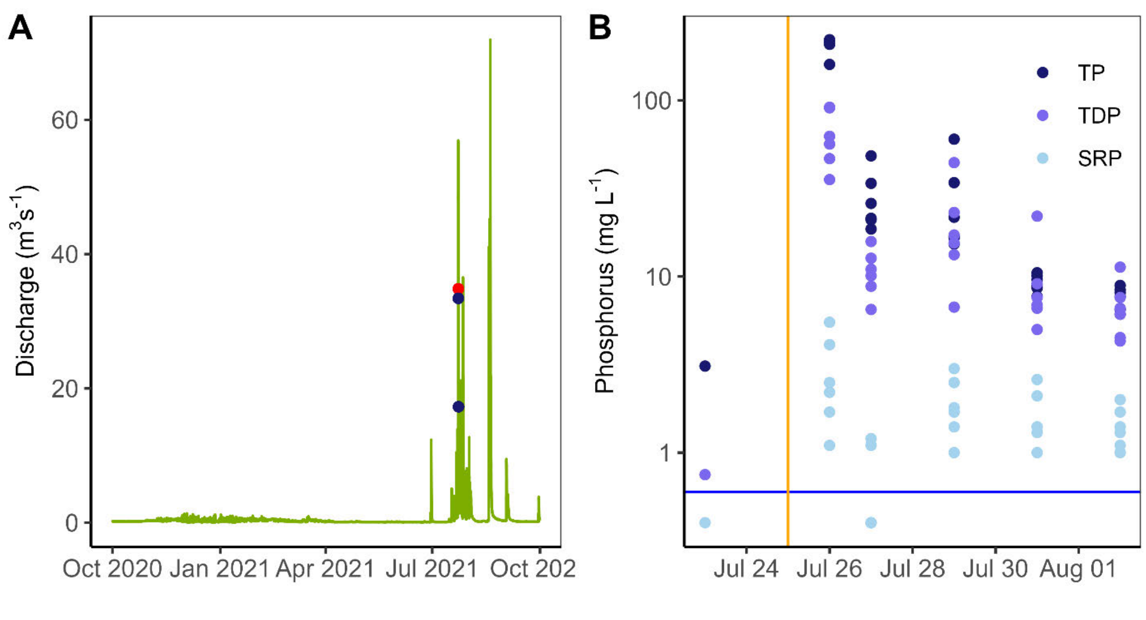

Figure 2. Annual discharge for water year 2021 at the USGS gage Paria River at Lees Ferry, AZ, 09382000 (U.S. Geological Survey, 2022) (A) and water column P concentrations from bottles incubated for 1 week (B). In panel A, the red dot shows the time when samples were collected for the 24-hour incubations (described above); the two blue dots show sample collection times for the week-long incubation (described here). Panel B shows water column concentrations of total phosphorus (TP, dark blue), total dissolved phosphorus (TDP, purple), and soluble reactive phosphorus (SRP, light blue) prior to amendment with Paria River storm water (left of orange vertical line) and post amendment during the week-long incubation. SRP detection limit is plotted as a blue horizontal line and samples that came back below the detection limit are plotted at ½ the detection limit. Note the log scale on the y axis in panel B. Taken from Deemer and others, submitted. Preliminary data, do not cite.

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 fish in the Grand Canyon (e.g., humpback chub; *Gila cypha* and flannelmouth sucker; *Catostomous latippinis*) under laboratory conditions. These fish 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. Personnel changes have caused this project to be delayed, but we are working on plans to complete this work in FY 2023.

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.

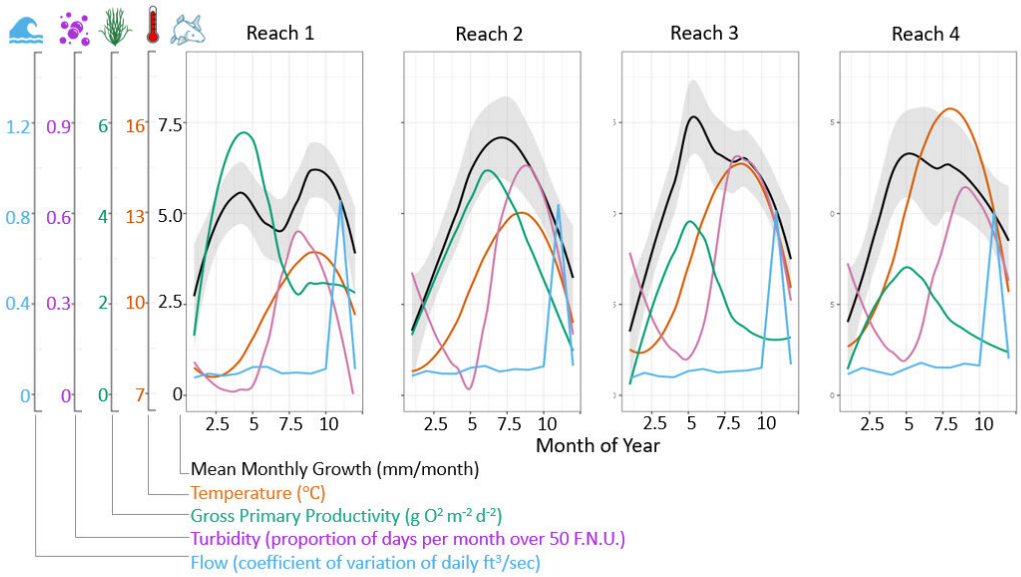

Figure 3. Smoothed predicted mean monthly growth in length (mm·month-1; black line) for a 200 mm flannelmouth sucker for four reaches across month intervals together with mean values of environmental covariates: temperature (orange line), GPP (green line), turbidity (purple line), and flow (blue line). 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. From Hansen and others, submitted. Preliminary data, do not cite.

A manuscript was submitted in which flannelmouth sucker growth is modeled as a function of gpp and water temperature (Hansen and others, submitted). The paper finds that variation in gpp is a significant driver of flannelmouth sucker growth (Figure 3). 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, submitted). This work represents a first step in developing ecosystem models to address questions about metabolic demand. We are working to develop models of humpback chub growth that are similar to the models built for flannelmouth sucker. These models will quantify relationships between humpback chub growth and gpp and temperature in both the Juvenile Chub Monitoring-east (JCM-east) and JCM-west reference reaches.

A second manuscript describes an approach to estimate prey production rates in Lees Ferry rates 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 (Yard and others, 2023; Korman and others, 2022). Overall, we continue to make progress in better understanding drivers of ecosystem productivity and linkages between ecosystem productivity and numerous LTEMP resources including native fish and the rainbow trout fishery.

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Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., *submitted*, 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.

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, online, https://doi.org/10.1139/cjfas-2022-0142.

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Project E Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$200,851	$10,500	$17,272	$14,500	$0	$28,615	**$271,738**
Actual Spent	$178,114	$3,893	$21,314	$5,000	$0	$25,211	**$233,532**
(Over)/Under Budget	**$22,737**	**$6,607**	**($4,042)**	**$9,500**	**$0**	**$3,404**	**$38,206**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$38,206**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to HR-delays in hiring and staff turnover.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is for purchases of necessary lab equipment.
- Underspent funds in Cooperative Agreements is due to funds obligated in FY22 that will be expended in FY23.

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

Presentations:

Bruckerhoff, L., Wheeler, K., Dibble, K., Mihalevich, B., Neilson, B., Wang, J., Yackulic, C., and Schmidt, J., 2022, Water storage decisions and consumptive use constrain ecosystem management under severe sustained drought—virtual presentation: Desert Fishes Council 2022 Annual Meeting, St. George, Utah.

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Dibble, K.L., 2022, 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, Flagstaff, AZ.

Dibble, K.L., Bruckerhoff, L.A., Yackulic, C.B., Schmidt, J.C., Bestegen, 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—Oral presentation and virtual panel for the Department of Interior's Turbine Talk Webinar Series focused on 'USGS Science on Climate Impacts on Hydropower'.

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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 (JASM 2002), Grand Rapids, MI.

Journal Articles:

Deemer, B.R., Reibold, R., Fatta, A., Corman, J.R., Yackulic, C.B., and Reed, S.C., *submitted*, pH of dam releases affects downstream phosphorus cycling in an arid regulated river: Ecological Applications.

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.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., *submitted*, 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.

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, online, https://doi.org/10.1139/cjfas-2022-0142.

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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.

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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
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Goals and Objectives

The principal goal of our work this year was monitoring invertebrate population response to the Macroinvertebrate Production Flows (Bug Flows) experiment that occurred on weekends from May-August 2022. To monitor the food base and invertebrate populations 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. We 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 2022, we also began new diet studies on native fish using non-lethal methods that include environmental DNA (eDNA) analysis of fish feces and stable isotope analysis of fish fin clips. We used entirely non-lethal methods for quantifying fish feeding habits to honor Tribal concerns about the taking of life.

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 trends in humpback chub (Project G) and 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).

Science Questions Addressed & Results

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 1). In 2022, community science sampling yielded 606 light trap samples of adult aquatic insects spanning more than 285 miles of the Colorado River, from April-October. Analysis of the 2022 light trap samples was presented at the Annual Reporting Meeting in January 2023. These data are being compared to light trap catches from prior years to evaluate effects of experimental Bug Flows, changing environmental conditions, and other factors on aquatic insect abundance throughout Grand Canyon.

We launched one Grand Canyon river trip in April 2022 to quantify invertebrate drift concentrations approximately every ten miles throughout Glen, Marble, and Grand Canyons. These data will be compared to similar drift data that were collected annually in 2017-2021 to evaluate effects of the Bug Flows experiment on invertebrate assemblages and drift biomass. Processing of drift river trip samples from 2017-2021 has been completed and was presented at the Annual Reporting Meeting. As part of this annual river trip, drift is collected at juvenile humpback chub monitoring locations (Little Colorado River confluence and Fall Canyon). Dissolved oxygen sensors (Mini-DOTs) for monitoring gross primary production (in support of Project E) are also cleaned and maintained on this trip. Collaborators from Oregon State University also participated to collect eDNA samples from tributary and mainstem locations and evaluate suitability of this new method for quantifying diversity and species richness of invertebrate assemblages (see F.3, Invertebrate monitoring in Tributaries, below).

In 2022, community scientists collected acoustic bat activity data paired with 262 of the light trap samples. Paired bat acoustic and insect monitoring data from 2017-2020 have been analyzed and revealed that bat activity (# of calls per hour) was positively related to the abundance of aquatic flies (Diptera) in Grand Canyon. Furthermore, aquatic flies as a predictor outcompeted all other invertebrate prey categories (e.g., moths, terrestrial insects) and environmental variables (e.g., vegetation cover, lunar phase, air temperature) in our models. We submitted a manuscript describing these findings in September of 2022 (Metcalfe and others, in review), and it has been tentatively accepted pending revision.

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. 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 2022 was comprised entirely of Tribal youth participants.

Element F.2. Invertebrate Monitoring in Glen Canyon

In FY 2022 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). In support of monitoring the Bug Flows experiment, we conducted two additional intensive sampling bouts that entailed collecting drift, sticky trap, and light trap samples daily during routine weekday hydropower fluctuations and steady low Bug Flows releases (i.e., daily sampling on a Friday through Monday). These intensive sampling bouts occurred from May 13-16 and June 10-13, 2022. Collectively, these data will allow us to track invertebrate populations in the Lees Ferry sport fishery using a variety of sampling methods and on robust spatial and temporal scales. Although monthly sample collections occurred as planned in 2022, laboratory sample processing is ongoing and results were not available at January's Annual Reporting Meeting.

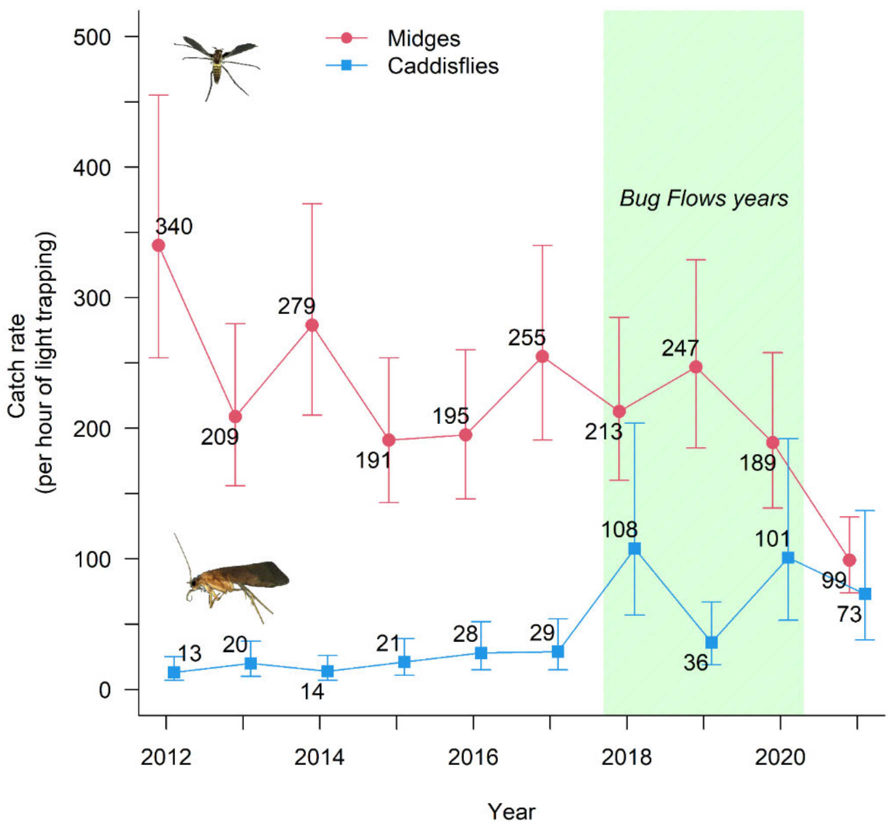

Figure 1. Average caddisfly (blue line) and midge abundance (red line) collected in community science light traps from 2012 through 2021. Annual average values appear above each point and are estimated from a mixed-effects model that accounts for variation in sampling effort across reaches and across years. Error bars represent one standard error. The abundance of caddisflies increased by ~400% during two of three years of Bug Flows experimentation (2018-2020) compared to the pre-Bug Flows baseline from 2012-2017. The abundance of midges was also predicted to increase with Bug Flows, but no such increase was detected during 2018-2020. However, in 2021 when Bug Flows were paused, midge abundance declined by 50 percent (a statistically significant decline) while caddisfly abundance remained unchanged (not statistically different) from the year prior.

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 2018 and 2020. We sampled aquatic invertebrates in Bright Angel Creek once in FY 2022. 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. We have been conducting these sampling trips since 2016 and now have a data set that spans multiple years of trout removal in addition to humpback chub reintroduction. This work will allow us to explore how the food web in Bright Angel Creek has responded to these management actions and what invertebrate food may be available for the translocated humpback chub. Analysis of these data is ongoing, and a manuscript describing these studies is under development.

Unregulated tributaries within the Grand Canyon have the potential to act as sources of invertebrate biodiversity for the mainstem, although the degree to which this occurs is unknown. To address this question of invertebrate diversity in mainstem 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 mainstem. Collaborators at Oregon State collected eDNA samples from 36 locations in the Grand Canyon corresponding to 18 paired mainstem and tributary locations in 2021. In 2022, 42 locations (21 pairs of sites) were sampled. Samples from the 2021 campaign have been processed while 2022 samples are still being processed. Diptera were the most common insect order in both mainstem and tributary locations, representing 62% of the identified OTUs. Non-metric multi-dimensional scaling ordination of sample sites shows a distinct grouping of mainstem and tributary sites, with statistically significant differences in both aquatic invertebrate community composition and variability within each group. Additionally, both tributary and mainstem groups show a shift in community composition associated with downstream distance from Glen Canyon Dam. These findings highlight the importance of Grand Canyon tributaries for preserving aquatic invertebrate biodiversity and reveal a wide diversity of Diptera that has previously been underrepresented in morphological taxonomy. Furthermore, this work demonstrates the utility of eDNA as a tool for monitoring invertebrate communities in the Grand Canyon.

Element F.4. Fish Diet Studies

Element F.4 includes analysis of existing rainbow and brown trout diet data from Lees Ferry. It also includes collection of new diet samples for native fish in Grand Canyon. In FY 2022, we collected samples of fish fin clips for stable isotope analysis on a seasonal basis. Stable isotope analysis of fin clips provides insights into feeding habits of fish. Sample totals were 349 fin clips from flannelmouth sucker and 104 fin clip samples from humpback chub. In FY 2022, we also collected fecal samples from native fish on a seasonal basis.

These fecal samples will be analyzed using the same eDNA laboratory process at Oregon State University that has been successful at identifying invertebrate communities from water samples (see Element F.3, above). This will provide detailed information on invertebrate species that are being consumed by native fish. Samples totals for FY 2022 include 239 flannelmouth sucker feces and 49 humpback chub feces.

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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.

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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 F Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$503,666	$15,283	$37,810	$0	$0	$68,626	**$625,385**
Actual Spent	$537,820	$13,728	$42,304	$0	$0	$73,198	**$667,051**
(Over)/Under Budget	**($34,154)**	**$1,555**	**($4,494)**	**$0**	**$0**	**($4,572)**	**($41,666)**
FY21 Unspent Funds	**$17,816**					**FY22 Unspent Funds**	**($23,850)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Overspent Salaries is due to promotions among staff and overtime associated with Bug Flow field studies and fall seining trip.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is for payments to community science participants and purchase of additional drift sampling equipment needed to provide JCM trips with their own gear for collection on trips.

Project F Deliverables: Aquatic Invertebrate Ecology

Presentations:

Kennedy, T., 2022, Background and design of the Bug Flows hydrograph—virtual presentation: Science Advisor review of the Bug Flow experiment, Day 1, October 2022.

Kennedy, T., 2022, Bug Flows and the rainbow trout fishery—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 1, October 2022.

Kennedy, T., 2022, Discussion of the Bug Flow synthesis and review and opportunities for Spring and Summer Flow Experiments—virtual presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, January 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T., 2022, Potential next steps in flow experimentation—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 2, November 2022.

Kennedy, T., and Muehlbauer, J., 2022, Project F—Aquatic ecology and food base monitoring—virtual presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 11-12, 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T. and Muehlbauer, J., 2022, Project F—Aquatic ecology and food base monitoring—virtual presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T.A., Muehlbauer, J.D., Deemer, B.R., Yackulic, C.B., Ford, M.A., Szydlo, C., Metcalfe, A.N., and Lytle, D.A., 2022, Experimental Bug Flows increase algae production and insect diversity in the Colorado River, Grand Canyon—presentation: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

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Metcalfe, A.N., Kennedy, T., Muehlbauer, J.D., Dodrill, M.J., Weller, T., Durning, L., Sankey, J.B., and C.A. Fritzinger, 2022, Insectivorous bat foraging along the Colorado River in Grand Canyon is determined by aquatic prey availability and tall vegetation density—presentation: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Muehlbauer, J., 2022, Bug Flows—Invertebrate response—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 1, October 2022.

Traynham, L. and Kennedy, K., 2022, "Potential LTEMP experiments Spring/Summer 2022—virtual presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, April 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

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.

Kennedy, T.A., Metcalfe, A.N., Deemer, B.R., Ford, M.A., Szydlo, C.M., Yackulic, C.B., and Muehlbauer, J.D., 2022, Little bugs, big data, and Colorado River adaptive management—Preliminary findings from the ongoing bug flow experiment at Glen Canyon Dam: Boatman's Quarterly Review, v. 35, no. 3, p. 26-31. (Not available online)

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

Project Lead	Charles B. Yackulic	**Principal Investigator(s)** (PI)	Maria Dzul, USGS, GCMRC Charles B. Yackulic, USGS, GCMRC Mariah Giardina, USGS, GCMRC Kirk Young, USFWS Randy Van Haverbeke, USFWS David Ward, USGS, GCMRC Laura Tennant, USGS, GCMRC
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Goals and Objectives

- Accurately estimate the abundance of various life stages (e.g., juveniles, subadults, adults) of humpback chub to inform triggers associated with the 2016 Biological Opinion (U.S. Department of the Interior, 2016b).
- Use models to learn about relationships between environmental factors and humpback chub 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 humpback chub abundances.

Project Elements

Element G.1. Humpback Chub Population Modeling

Science Questions/Hypotheses Addressed

In FY 2022, model development focused primarily on answering the following scientific questions: 1) how do survival and growth rates in western Grand Canyon compare to those of humpback chub (*Gila cypha*) in the Little Colorado River aggregation? and 2) can we use detections from a multiplexer array (see project G.4) to improve abundance estimation in the Little Colorado River? In addition to these two model development projects, we also used our established models of humpback chub in the Little Colorado River aggregation to learn whether or not abundance estimates in the Little Colorado River aggregation were above biological triggers, which are linked to management actions such as trout removals (U.S. Department of the Interior, 2016a).

Results

Results from the JCM-west model will be included in a manuscript that is expected to be submitted to a scientific journal early in FY 2023. We have developed and fit a novel model that integrates the multiplexer data alongside standard sampling and are conducting simulations to ensure estimates are unbiased. We will continue development of this model in FY 2023. The multistate model for annual reporting in FY 2021 indicated that chub adult abundances remained above 9,000 and the U.S. Fish and Wildlife Service (USFWS) estimate of the running 3-year average of large subadults in the Little Colorado River was greater than 1,250. However, due to a low 3-year running average of subadult abundance in the JCM-east reach (mean abundance less than 810), we were in Tier 1 for biological triggers (U.S. Department of the Interior, 2016a) in FY 2021. Abundances for 2022 associated for biological triggers (currently being estimated) will be reported at the annual reporting meeting.

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

This is part of a long-term monitoring program with the goal to monitor the population status and trends of humpback chub in the Little Colorado River to help answer these questions:

- What are the length-stratified abundance estimates of humpback chub (e.g., > 100 mm, ≥ 150 mm, ≥ 200 mm TL) in the lower 13.6 km of the Little Colorado River during the spring and fall?
- What does this imply for population trends?”

Abundance estimates from these monitoring efforts are used to inform actions and triggers associated with the 2016 Biological Opinion (U.S. Department of the Interior, 2016b).

Results

In 2022, USFWS and volunteers conducted four monitoring trips (during April, May, September, and October) to monitor humpback chub in the Little Colorado River. During spring 2022, we estimated that there were 10,500 (Standard Error [SE] = 700) humpback chub ≥ 150 mm total length (TL), of which 8,500 (SE = 700) were ≥ 200 mm TL in the Little Colorado River (Figure 1). These numbers represent a significant increase from the spring 2021 estimates and were similar to 2019 estimates (2020 spring estimates were not obtained because of Covid impacts). In fall 2021, it was estimated that there were 3,800 (SE = 300) HBC ≥ 150 mm TL in the Little Colorado River. Of these fish, an estimated 1,900 (SE = 200) were ≥ 200 mm TL (Figure 1).

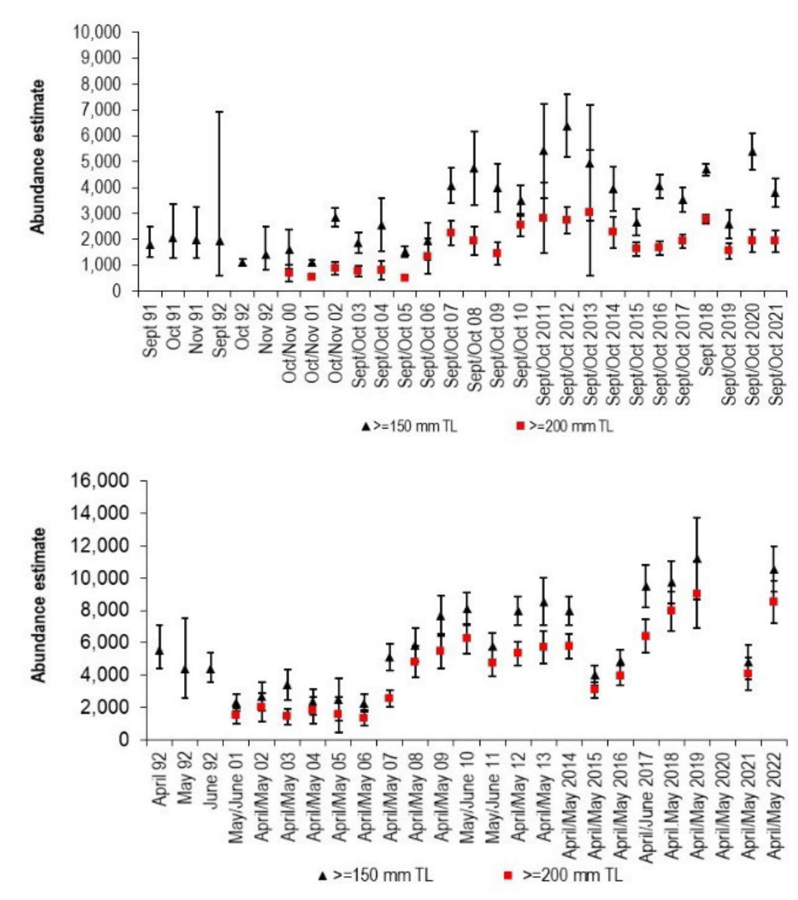

Figure 1. Chapman Petersen abundance estimates (±95% CI) of humpback chub ≥ 150 mm total length (TL) and ≥ 200 mm TL in the Little Colorado River (0-13.57 river km) during spring 2001-2022 (upper panel) and fall 2000-2021 (lower panel). Note: closed spring and fall abundance estimates of humpback chub > 150 mm TL in the Little Colorado River during 1991 and 1992 are from Douglas and Marsh (1996), and no spring 2020 estimates were obtained because of Covid impacts. Preliminary data, do not cite.

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

Science Questions/Hypotheses Addressed

- What are the abundance estimates of humpback chub in the Little Colorado River aggregation and what does this imply for population trends (increasing, stable, decreasing)?
- Which environmental conditions are favorable for humpback chub production in the Little Colorado River?
- Which environmental factors influence humpback chub outmigration from the Little Colorado River to the Colorado River?

Abundance estimates are used to inform triggers associated with the 2016 Biological Opinion (U.S. Department of the Interior, 2016b).

Results

In 2022, three sampling trips (in April, July, and October) were conducted in the JCM-east reach, and one June trip was conducted at the Little Colorado River. We caution that data reported here are provisional and have not been fully checked for quality control. Flannelmouth sucker (*Catostomus lattipinnis)* were the most frequently caught species in JCM-east catch (2491), followed by humpback chub (1443), fathead minnow (*Pimephales promelas)* (1037), rainbow trout (*Oncorhynchus mykiss)* (723), bluehead sucker (*Catostomus discolobus)* (388), channel catfish (*Ictalurus punctatus)* (210), plains killifish (*Fundulus zebrinus)* (51), carp (*Cyprinus carpio)* (33), black bullhead (*Ameiurus melas)* (28), speckled dace (*Rhinichthys osculus)* (27), brown trout (*Salmo trutta)* (7), yellow bullhead (*Ameiurus natalis)* (6), bluegill (*Lepomis macrochirus)* (1), red shiner (*Cyprinella lutrensis)* (1), and black crappie (*Pomoxis nigromaculatus)* (1). In total, all JCM-east trips captured 787 humpback chub > 79 mm TL and marked 642 humpback chub between (40-79 mm TL) with visual implant elastomer (VIE), a fluorescent pigment injected under the fishes' skin. Catch of humpback chub > 79 mm TL was 64 in May, 434 in July, and 289 in October. In addition, the number of humpback chub given a VIE (between 40-79mm TL) was 21 in April, 33 in July, and 588 in October. Age-0 abundance in the Little Colorado River in July was moderate in 2022 compared to 2013-2021 (Figure 2).

The large number (catch = 209) of channel catfish captured during the October 2022 trip represents an all-time high compared to previous years of JCM sampling (2012-2021), where previously the maximum catch of channel catfish occurred in April 2015 (catch = 12) followed closely by January 2015 (catch = 11), with other trips capturing between 0-6 catfish. Importantly, channel catfish captured during October 2022 were all 53-104 mm fork length.

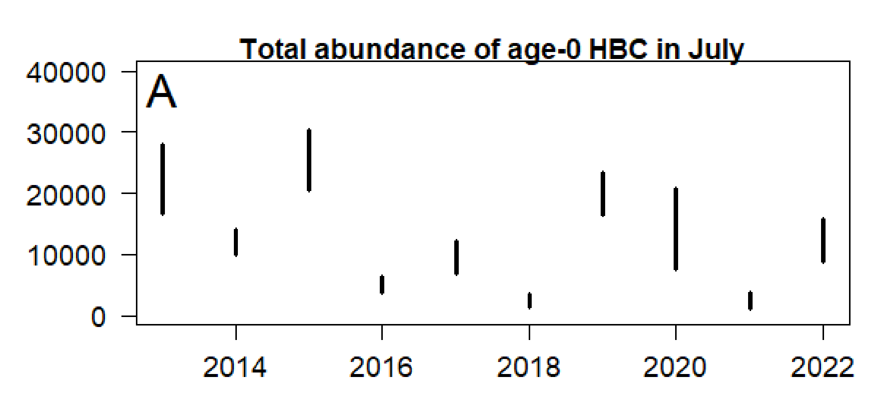

Figure 2. Estimated abundance of age-0 humpback chub (i.e., < 80 mm total length (TL)) during mid-summer sampling trips to the lower 13.6 km of Little Colorado River. Preliminary data, do not cite.

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

Science Questions/Hypotheses Addressed

- Can detection from remote passive integrated transponder (PIT)-tag arrays be used to improve estimation of abundance and movement for adult humpback chub?

- How does the number of adult humpback chub moving into the Little Colorado River (and presumably spawning in the Little Colorado River) fluctuate from year to year?
- How does movement timing for adult humpback chub vary from year to year and how does this influence estimation of adult abundance in the Little Colorado River?

Results

The multiplexer (MUX) is comprised of two arrays (in situ chains of PIT tag antennas that stretch across the river), located ~1.7 river kilometers (rkm) upstream of the confluence with the Colorado River; by convention, distances in the Little Colorado River are measured in kilometers upstream from its confluence with the Colorado River. The MUX can read PIT tags of fish that swim past it, offering an alternative method for detecting PIT tags that does not rely on physical capture. Detections from these antennas are used to supplement Little Colorado River sampling efforts to learn more about availability (i.e., probability migrating fish are in the Little Colorado River during USFWS sampling) and movement timing.

This new MUX system installed in November 2020 has shown very high detection probabilities over the last two years, detecting 7,700 unique tags (including 4,352 unique humpback chub tags) in spring 2021 (March 21-June 15) and 10,126 unique tags (including 5,406 unique humpback chub tags) in 2022 (February 15 – June 15). Preliminary results from a Little Colorado River -MUX detection model suggest that in 2022, the MUX detection probability (i.e., probability of being detected by at least one array) for marked, migrating humpback chub was 94% for upstream movement and 41% for downstream movement (Figure 3). Currently, the MUX is non-operational after flood damage in summer and fall of 2022, but plans to repair this system during winter 2022/2023 are currently in development.

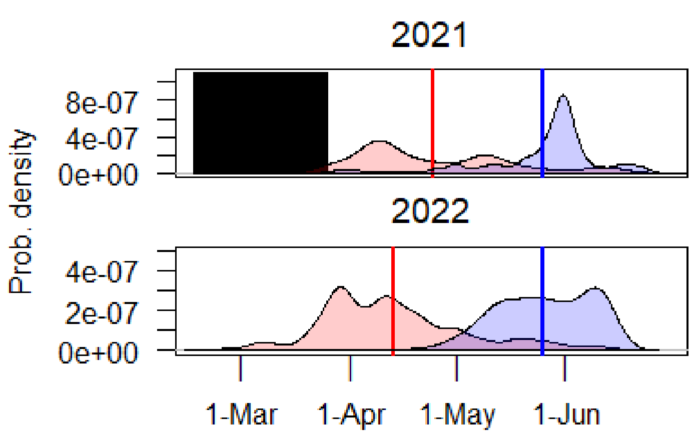

Figure 3. Probability densities of upstream movement (pink) and downstream movement (blue) detections in 2021 ($n_{upstream}$ = 1725, $n_{downstream}$= 326) and 2022 ($n_{upstream}$ = 2635, $n_{downstream}$= 172). Upstream and downstream detections were identified if a fish was detected on both the upstream and downstream array and these detections occurred within one hour of each other. The red and blue vertical lines correspond to the mean upstream and downstream movement dates, respectively. Data from February 15-March 21 were lost due to a data backup error (black shaded; unpublished data).

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

Science Questions/Hypotheses Addressed

- What are trends in long-term (catch-per-unit effort (CPUE)) and(or) abundance of humpback chub in the historical "aggregation" sites (Valdez and Ryel, 1995) as well as throughout western Grand Canyon?

Results

The results presented here are relevant up to 2021, because mainstem aggregation data for 2022 are still being analyzed. A substantial increase in the abundance of humpback chub has occurred in western Grand Canyon, beginning with spikes of age 0 humpback chub in 2014 that translated into substantial increases in the adult population starting in 2017 (Figure 4). This increase in adults is thought to be caused by increases in water temperature, which exceeded ~19 °C in 2014, and were within suitable spawning temperatures for humpback chub. 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 clear signal of a substantial population of adult humpback chub present between Pumpkin Spring and Separation Canyon (~RM 210-240). Densities appear to diminish downriver from Separation Canyon (below ~RM 240). Nevertheless, densities are 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 (Van Haverbeke and others, in prep.)

Additionally, we conducted opportunistic seining in 2021. We seined 91 backwaters between RM 35.6 and 269.2. Fish captures included 3,517 fish, of which 459 were humpback chub. Most humpback chub captured with seines were age 0 fish ≤ 70 mm. Seven nonnative species were captured, including five green sunfish (*Lepomis cyanellus*) captured at RM 159.3, RM 165.2 (3 fish), and RM 199.5. We consider seining to be an important tool for early detection of juvenile nonnative fish.

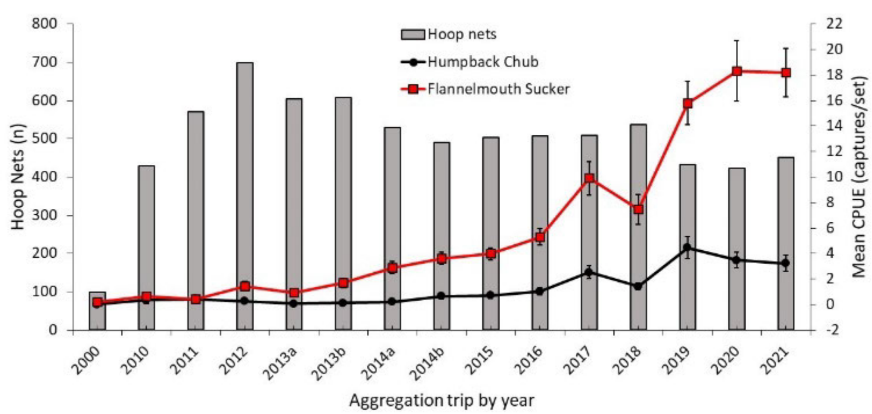

Figure 4. CPUEs of humpback chub (*Gila cypha)* and flannelmouth sucker (*Catostomus latipinnis),* all size classes, paired with total hoop nets set for each Grand Canyon aggregation trip 2000, and 2010-2021. Note in 2013 and 2014, two hoop netting aggregation trips [July (a), and September (b)] were conducted. Preliminary data, do not cite.

Element G.6. Juvenile Humpback Chub Monitoring – West

Science Questions/Hypotheses Addressed

Humpback chub in western Grand Canyon are a relatively new component of humpback chub population in Grand Canyon, and little is known about their vital rates (survival, growth, movement, recruitment, abundance).

- How do survival rates of humpback chub in western Grand Canyon compare to those of the Little Colorado River aggregation?
- What are humpback chub abundances in western Grand Canyon and what do they imply for population trends?

Results

The JCM-west reach (located 210.5-214 river miles downstream of Lees Ferry) was sampled three times (May, July, and October) in 2022 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 similar for JCM-west and JCM-east reach (see Project Element G.3), and data presented are provisional and have not been subjected to full quality control. Species composition of catch in JCM-west was comprised mostly of native species, with the highest catch occurring for flannelmouth sucker (7008), speckled dace (5109), humpback chub (3105), and bluehead sucker (1442). Nonnative catch was comprised of fathead minnow (103), rainbow trout (53), common carp (15), green sunfish (12), striped bass (*Morone saxatilis)* (5), brown trout (5), walleye (*Sander vitreus)* (2), plains killifish (2), yellow bullhead (1), and black bullhead (1). In the JCM-west reach, catch of humpback chub > 79 mm TL was 222 in May, 240 in July, and 417 in October. In addition, the number of humpback chub issued VIE marks between 40-79 mm TL was 45 in May, 139 in July, and 1295 in October. In 2022, we wrote a manuscript describing humpback chub population dynamics in the JCM-west reach from 2017-2021 that we will submit to a scientific journal early in FY 2023 (Dzul and others, in prep).

Element G.7. Chute Falls Translocations

Science Questions/Hypotheses Addressed

The goals of this project, conducted by the USFWS, are to evaluate the potential for translocations to increase/maintain adult abundance in the Little Colorado River aggregation, by increasing growth, survival, and expanding the geographic distribution of humpback chub. This project is identified as a Conservation Measure in the LTEMP Biological Opinion (U.S. Department of the Interior, 2016b). These monitoring activities also coincide with collaborative efforts with the National Park Service (NPS) to collect juvenile or larval HBC for transport to the Southwest Native Aquatic Research and Recovery Center (SNARRC).

Results

Project Element G.7 annually translocates at least 300 juvenile humpback chub from lower portions of the Little Colorado River to upstream of rkm 14.2 (i.e., upstream of Chute Falls), and annually monitors the abundance of humpback chub upstream of rkm 13.6 in the Little Colorado River to evaluate the effectiveness of translocations.

Efforts to translocate humpback chub upstream of Chute Falls in the Little Colorado River have been ongoing since 2003. To date (as of October 28, 2022), approximately 4,874 juvenile humpback chub have been translocated upstream of Chute Falls. Of these, 198 were released above Chute Falls (at rkm 16.2) on October 28, 2022. No fish were collected for translocations into Havasu, Bright Angel, or Shinumo Creeks during 2022, given perceived low young-of-year (YOY) production (lack of fish available). In May 2022, it was estimated there were 572 humpback chub ≥ 100 mm (SE = 25) in the Atomizer reach (~rkm 13.6-14.1), of which 307 (SE = 15) were ≥ 200 mm (Figure 11-A). Likewise, in May 2022, it was estimated there were 621 humpback chub ≥ 100 mm (SE = 99) in the Chute Falls sample reach (~rkm 14.1-17.6), of which 379 (SE = 48) were ≥ 200 mm (Figure 5). Humpback chub translocations have been found to provide modest increases to adult humpback chub abundances and, in some situations, may provide a good alternative to trout removals (Yackulic and others, 2021)

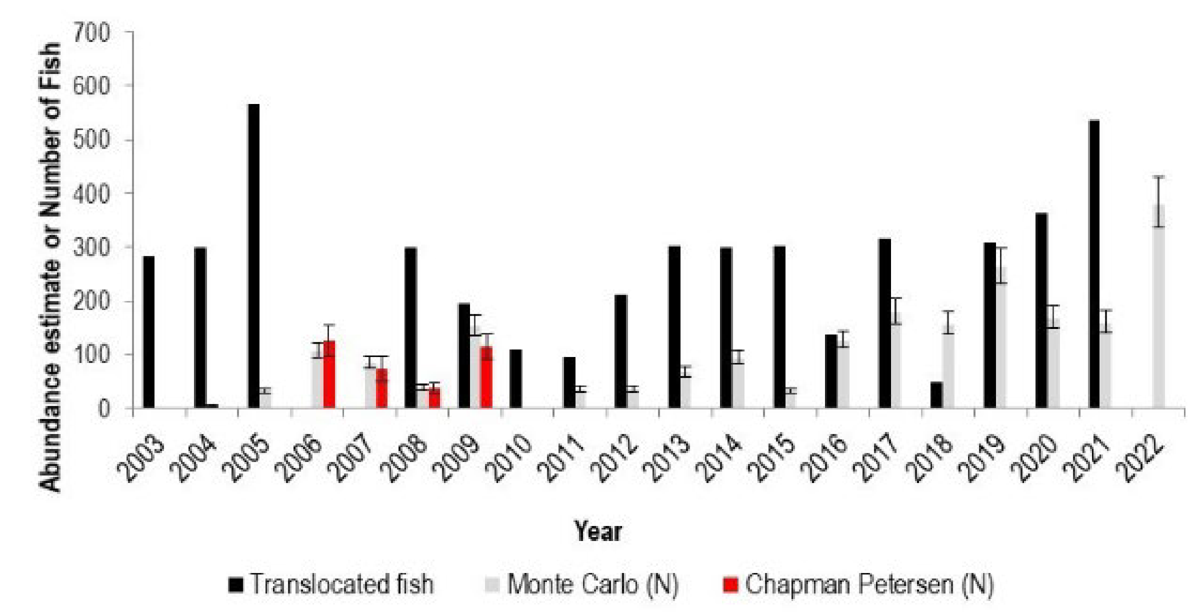

Figure 5. Numbers of juvenile humpback chub translocated to the Chute Falls (rkm 14.1-17.7) reach since 2003 (black bars); and abundances of adult humpback chub ≥ 200 mm in the Chute Falls reach estimated with Chapman Petersen method (red bars), and Monte Carlo simulation (light gray bars). Preliminary data, do not cite.

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Douglas, M.E., and Marsh, P.C., 1996, Population estimates/population movements of *Gila cypha*, an endangered cyprinid fish in the Grand Canyon region of Arizona: Copeia, v. 1996, no. 1, p. 15-28, https://doi.org/10.2307/1446938.

Dzul, M.C., Yackulic, C.B., Giardina, M., Yard, M., Van Haverbeke, D.R., *in prep,* Vital rates of a burgeoning population of humpback chub in western Grand Canyon.

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Valdez, R.A., and Ryel, R.J., 1995, Life history and ecology of the humpback chub (*Gila cypha*) in the Colorado River, Grand Canyon, Arizona—final report to Bureau of Reclamation: Salt Lake City, Utah, BIO/WEST, Inc., BIO/WEST report no. TR-250-08, Contract no. 0-CS-40-09110, 328 p. plus appendices. (Available upon request from GCMRC)

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 12.326%	Total
Budgeted Amount	$343,451	$4,000	$79,500	$520,766	$0	$68,249	**$1,015,966**
Actual Spent	$316,378	$1,731	$75,153	$520,766	$0	$64,097	**$978,126**
(Over)/Under Budget	**$27,073**	**$2,269**	**$4,347**	**$0**	**$0**	**$4,152**	**$37,840**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$37,840**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Underspent in Operating Expenses due to Pit Tags being purchased through BOR instead of the project.

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

Presentations:

Bair, L.S., 2022, Adaptive management and cultural ecosystem services—virtual presentation: ACES, A Community on Ecosystem Services Conference, December 2022.

Bair, L.S., 2022, Consideration of plural values in integrated assessments—presentation: AGU Chapman Conference, on 'Solving Water Availability Challenges through an Interdisciplinary Framework', September 12-16, 2022.
Dzul, M.C., and Yackulic, C.B., 2022, Effects of flow, sediment, and nonnative fishes on age-0 population dynamics of humpback chub in the lower Little Colorado River—presentation: 16th Biennial Conference of Science and Management for the Colorado Plateau and Southwest Region, September 12-15, 2022, Flagstaff, AZ.

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., Bair. L.S., *in prep*, The economic cost of designer flows in river conservation.
Dzul, M.C., Yackulic, C.B., Giardina, M., Yard, M., Van Haverbeke, D.R., *in prep,* Vital rates of a burgeoning population of humpback chub in western Grand Canyon.
Van Haverbeke, D.R., Dzul, M.C., Yackulic, C.B., Young, K.L., *in prep*, Abundance estimation of a recent prodigious humpback chub population in western Grand Canyon.

USFWS Reports:

Van Haverbeke, D.R., Young, K.L., Pillow, M.J., and Rinker, P.N., 2022, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2021: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey Grand Canyon Monitoring and Research Center, 49 p.
Van Haverbeke, D.R., K.L. Young, M.J. Pillow, and Rinker, P.N., 2022, Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2021: Flagstaff, Ariz., U.S. Fish and Wildlife Service, USFWS Document no. USFWS-AZFWCO-22-04, 41 p.

Project H: Salmonid Research and Monitoring

Project Lead	Charles Yackulic	**Principal Investigator(s)** (PI)	Charles Yackulic, USGS, GCMRC Josh Korman, Ecometric Research Mariah Giardina, USGS, GCMRC David Rogowski, AZGFD David Ward, USGS, GCMRC Molly A.H. Webb, USFWS James A. Crossman, BC Hydro
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Goals and Objectives

This project is designed to evaluate the response of rainbow trout *(Oncorhynchus mykiss)* and brown trout *(Salmo trutta)* to both 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 has been 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), brown trout early life stage survey results (H.3), and ongoing population modeling (H.4) developed from data collected primarily through H.2.

Project Elements

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

Science Questions/Hypotheses 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.

Methods

We conduct boat electrofishing at randomly selected 250-meter (m) 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 warm water nonnative sampling during summer and autumn sampling trips to detect warm-water nonnative species, as described 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 six 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 fish 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 2022, sampling 120 sites and capturing 1,429 fish (excluding the nonnative sampling); 873 rainbow trout (*Oncorhynchus mykiss*), 377 brown trout (*Salmo trutta*), 105 flannelmouth sucker (*Catostomus latipinnis*), 14 smallmouth bass (*Micropterus dolomieu*), three black crappie (*Pomoxis nigromaculatus*), two common carp (*Cyprinus carpio*), and two green sunfish (*Lepomis cyanellus*). Rainbow trout CPUE (0.87 fish/minute [0.75, 0.98]) was similar to 2021 (0.87 fish/minute [0.70, 1.0]) and continues to be the lowest we have observed since monitoring began in 1991 (Figure 1). Rainbow trout comprised 61.2% of our 2022 catch, and this is the lowest percentage of the fish assemblage we have ever measured. Brown trout CPUE (0.37 fish/minute [0.30,0.44]) was similar to 2021 (0.34 fish/minute [0.28, 0.42]). Brown trout catch rates for 2020-2022 have been higher than all previous years, with brown trout comprising 26.6% of our 2022 catch (Figure 2). Relative abundance of rainbow trout, as measured by electrofishing CPUE, has fluctuated greatly since AZGFD began standardized sampling in 1991 (Figure 1). However, from 2019 – 2022, rainbow trout CPUE declined, particularly among smaller size classes (< 152 mm, 152 mm – 305 mm). Large rainbow trout (> 306 mm) are less abundant than other size classes, but CPUE has remained relatively steady since 2016 (Figure 3). In fall, young of year accounted for 67% of the rainbow trout catch (compared to 74% in 2021), with a CPUE of 0.54 fish/hour (lower than 2021 at 0.75 fish/hour). Although rainbow trout abundance was low, the fish we captured showed a high relative condition in 2022, which was greater than 1.0 for all size classes across all sampling trips.

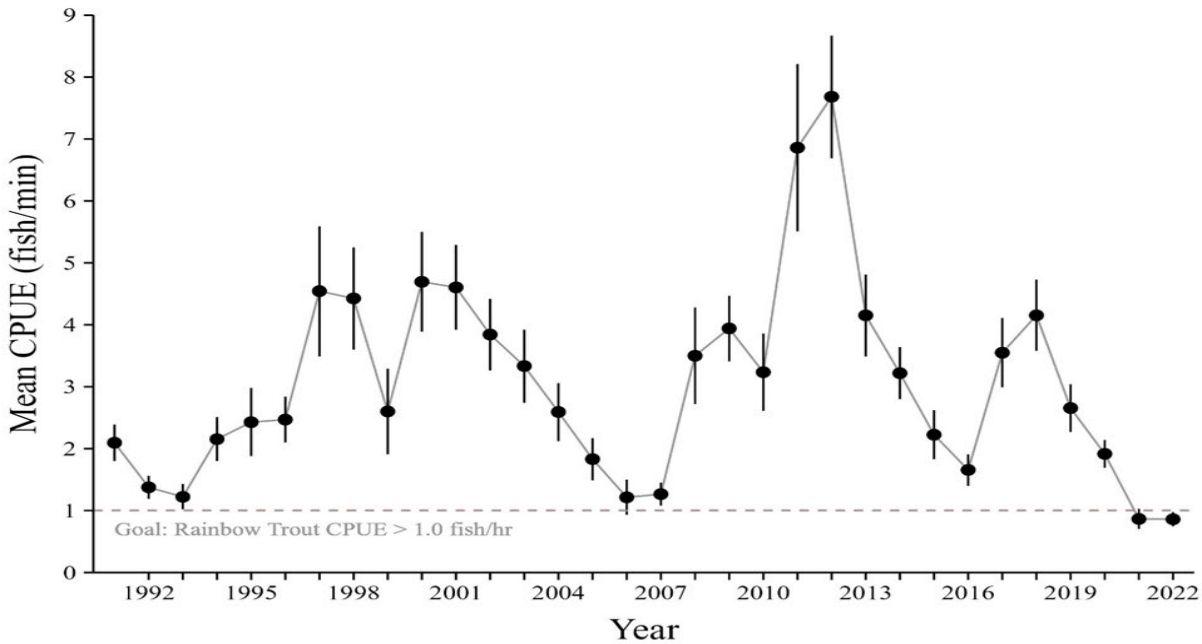

Figure 1. Average catch-per-unit-effort (fish/minute) of rainbow trout at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing) by year.

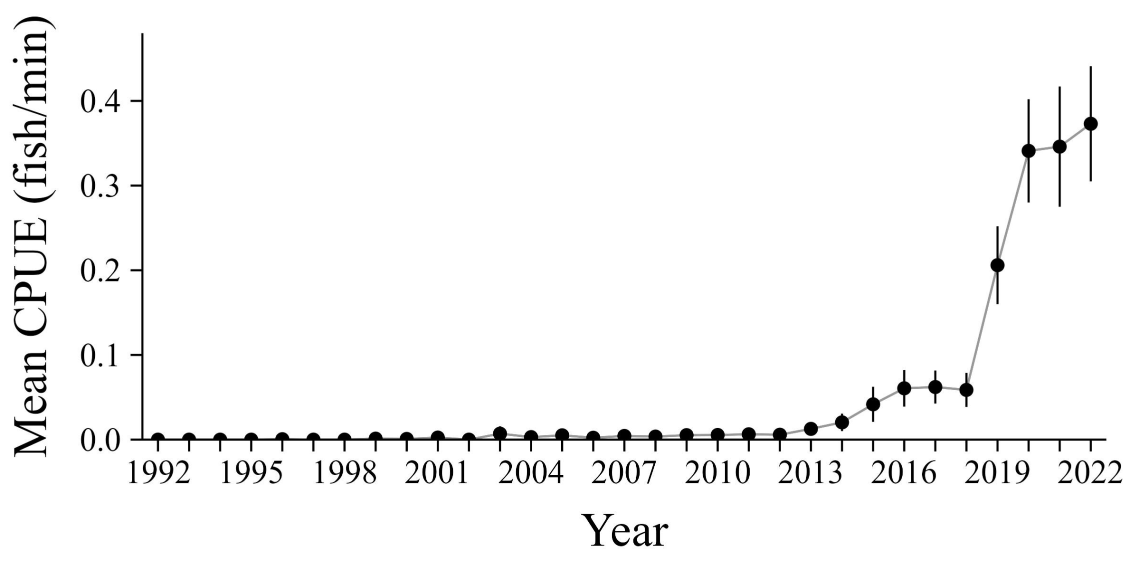

Figure 2. Mean catch-per-unit-effort (fish/minute) of brown trout captured during Arizona Game and Fish Department's monitoring at Lees Ferry by year. This represents the average across all size classes and reaches sampled.

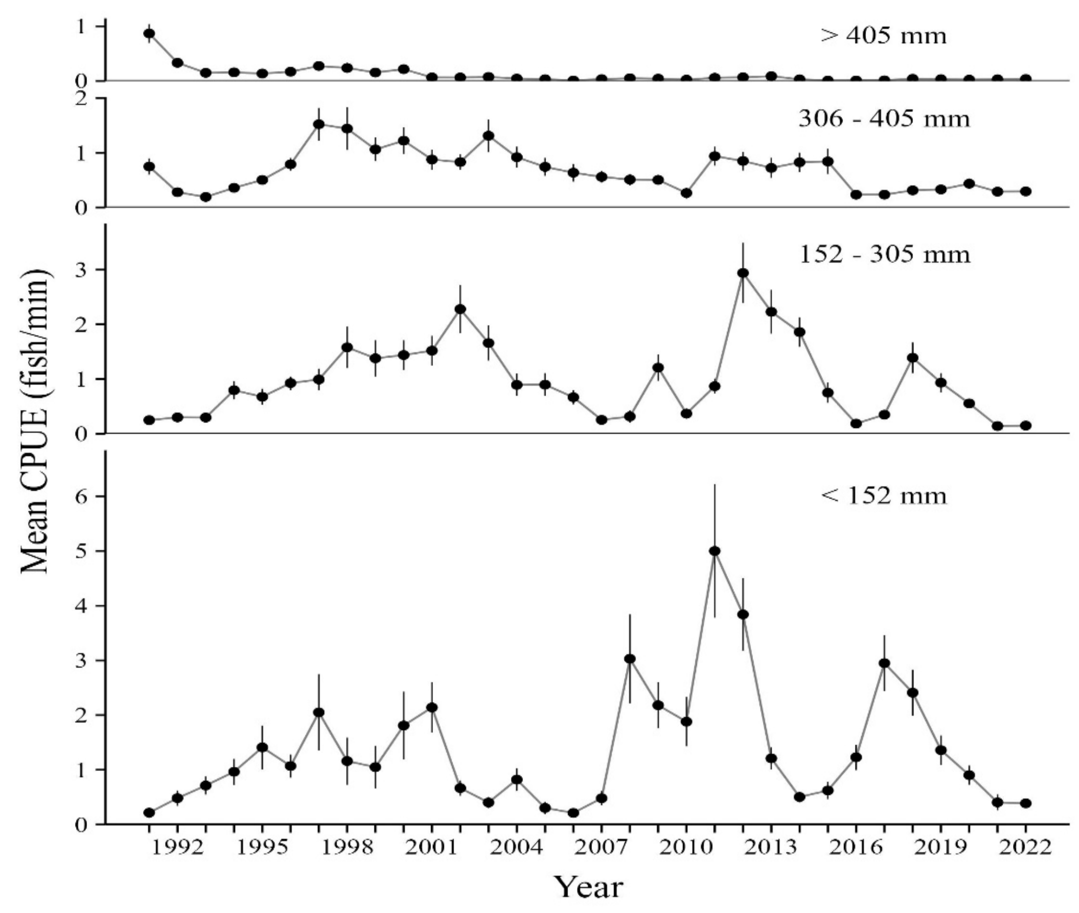

Figure 3. Average catch-per-unit-effort (fish/minute) of rainbow trout at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing) by size class and year.

Angler Surveys (Creel)

We report on creel data on a calendar year cycle and data collection is ongoing. For this report, we present data from January through early October 2022. We conducted angler surveys on 58 days and interviewed 595 boat anglers and 94 walk-in anglers. Angler catches rates (CPUE) for rainbow trout in 2022 for boat anglers was 0.74 fish/hour, and for walk-in anglers it was 0.52 fish/hour. Angler catch rates are below the AZGFD management goal for an angler catch rate of ≥ one rainbow trout per hour. Seventy percent of boat anglers and 38% 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 2022 (3.3) compared to 2021 (3.4). Boat angler satisfaction increased in 2022 (3.8) from 2021 (3.6). Although an incentivized harvest program for brown trout was implemented, harvest rates for brown trout were only 25% for boat anglers. Only four brown trout were captured in the walk-in area, and all were harvested. In 2022, 59% of unique anglers interviewed knew about the incentivized harvest program, and of those, 46% said they would participate. However, only 85 of 670 (12%) anglers interviewed captured a brown trout, and only 28 anglers harvested a brown trout. 33% of anglers that captured a brown trout harvested a brown trout.

Community Science Program

Data collection for this project is ongoing. For this report, we present data from January through September of 2022. Citizen scientists submitted length data on 719 rainbow trout and 50 brown trout captured. These data came from six private anglers with a total of 79 unique trips. These data are not representative of all anglers, as 70% percent of the angler trips were from one angler. Rainbow trout captured by citizen scientists had a mean length of 13.2 inches [13.2, 13.3] (337 mm [334, 339]), and brown trout had a mean total length of 16.7 inches [14.4, 16.4] (424 mm [404, 443]). Rainbow trout captured in 2022 were on average larger than those captured in 2021 (12.1 inches, 308 mm). Based on citizen science data, the rainbow trout fishery at Lees Ferry was not meeting AZGFD management goals for quality size fish; only 37% of angler trips resulted in anglers catching ten 14" rainbow trout in a 10-hour day (based on CPUE), and no angler trips caught rainbow trout 20" or greater (out of 79 trips).

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

Research Objectives Addressed

This research is referred to as the Trout Recruitment and Growth Dynamics (TRGD) project, and it is designed to collect data that is used to determine the impacts of environmental conditions and experimental flows on the recruitment of young-of-year (YOY) rainbow trout and brown trout in Glen Canyon, the growth rates of juvenile and adult trout, and dispersal of YOY trout from Glen Canyon to Marble Canyon. TRGD was established in the FY 2018-20 Triennial Work Plan (TWP; U.S. Department of the Interior, 2017) with three subreaches from Glen Canyon Dam to Lees Ferry, each with an assigned 3-km length. Due to budget constraints in the FY 2021-23 TWP, sampling effort was reduced to two subreaches (1A, 1C). The two remaining subreaches are in the upper (circa -12 RM) and lower (circa ~-4 RM) portions of Glen Canyon and represent 24% of the total shoreline length of Glen Canyon. The lowest subreach (1C) has been sampled since 2012, which allows for long term analyses (comparisons and contrasts) that integrate the Natal Origins (NO) Project (2011-2017; FY 2015-17 TWP; U.S. Department of the Interior, 2014) and more recent work plans (FY 2018-20 TWP), which informs both brown and rainbow trout models (Project Element H.4). During FY 2021-23, an additional focus of this project is on developing field techniques to measure reproductive condition more accurately in salmonids, with the potential to extend these noninvasive methods to native fish species once they have been refined. This element also involves sampling in Marble Canyon intended to inform our understanding of rainbow trout emigration from Lees Ferry.

Results

TRGD Sampling in Lees Ferry

In 2022, subreaches 1A and 1C were sampled in the months of January, April, September, and November, and subreach 1C was sampled a fifth time in June. Each sampling trip consisted of a 2-pass mark-recapture methodology using electrofishing as the gear type.

A total of 16,998 fish (rainbow trout [10,944]; brown trout [4,459]; flannelmouth sucker [1013]; green sunfish [446]; smallmouth bass [69]; bluegill sunfish [*Lepomis macrochirus*; 34]; common carp [28], black crappie [3]; bluehead sucker [*Catostomus discobolus*; 1] and walleye [*Sander vitreus*; 1]) were captured by electrofishing in 2022.

Rainbow trout catch in 2022 was low compared to historical data but was similar to 2021 catch (Figure 4). Brown trout catch remained relatively high in 2022 (compared to historical data for this species) but was lower than 2021 catch during the September and November trips (Figure 5). In particular, the fall catch of YOY brown trout (< 75 mm) was lower than in 2020 and 2021, suggesting lower brown trout recruitment in 2022. These declines in fall brown trout catch, while modest, coincided with the four warmest months in terms of water temperatures in the last fifty years, and dissolved oxygen was extremely low (with daily averages dropping below 3mg/L and point measurements as low as 2 mg/L) during this period (USGS gage 09380000; U.S. Geological Survey, 2022). These data could indicate either lower capture probability at warmer temperatures or a decline in the overall population.

Ongoing brown trout modeling under Element H.4 is attempting to disentangle these impacts. Past research has shown that changes in the condition of rainbow trout often precede population declines (Korman and others, 2016; Korman and others, 2017; Korman and others, 2020), and recent declines in the condition of both rainbow and brown trout during the four months of elevated temperatures (Figure 6) suggest the potential for future declines in abundance of both species. The decline in condition of brown trout was particularly notable, consistent with the decline in catch of brown trout. Analysis of rainbow and brown trout capture-recapture data under H.4 will occur over the next few months after the data have been processed .

While the Glen Canyon catch was dominated by salmonids, warm-water nonnatives like smallmouth bass, bluegill sunfish, and green sunfish increased substantially over the course of the year (from zero in 2021 to 69 in 2022 for smallmouth bass, zero in 2021 to 34 in 2022 for bluegill sunfish, and 15 in 2021 to 446 in 2022 for green sunfish). Sampling in both September and November suggested that abundances of warm-water nonnative species are higher in areas of Lees Ferry that are closest to the dam (e.g., 64 smallmouth bass have been captured in subreach 1A, which is within 3 miles of the dam, as compared to five smallmouth bass captured downstream in subreach 1C, which is more than 10 miles from the dam).

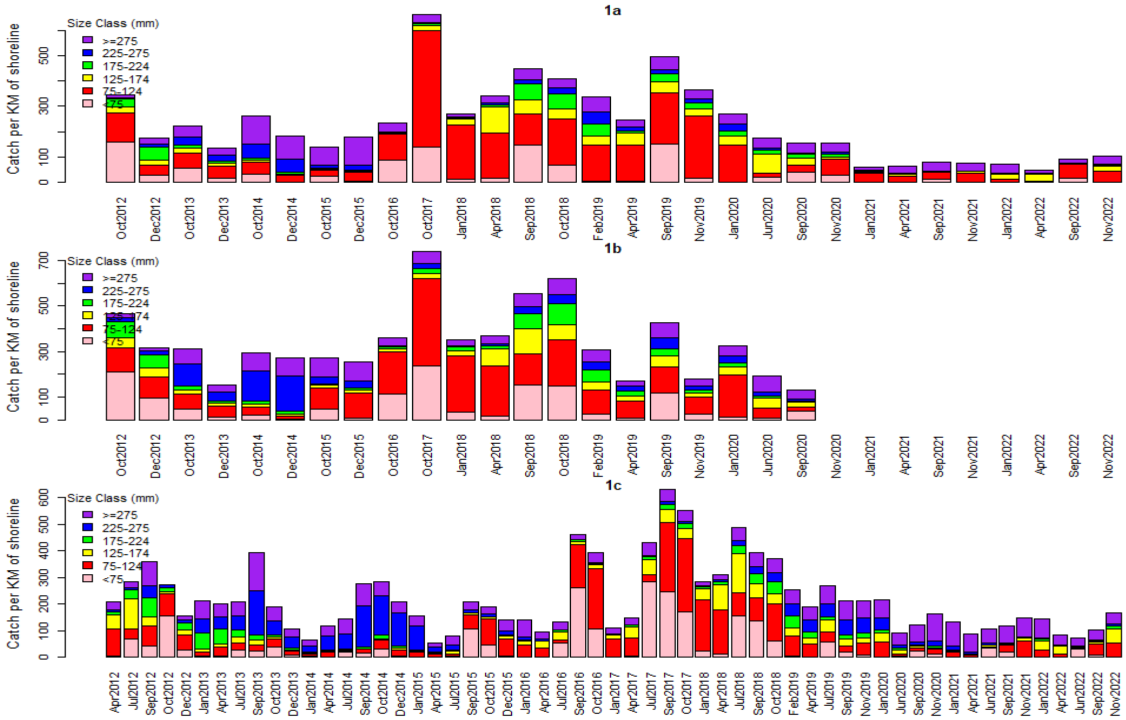

Figure 4. Rainbow trout catch per kilometer of shoreline over time in each subreach by size classes (colors). Preliminary data, do not cite.

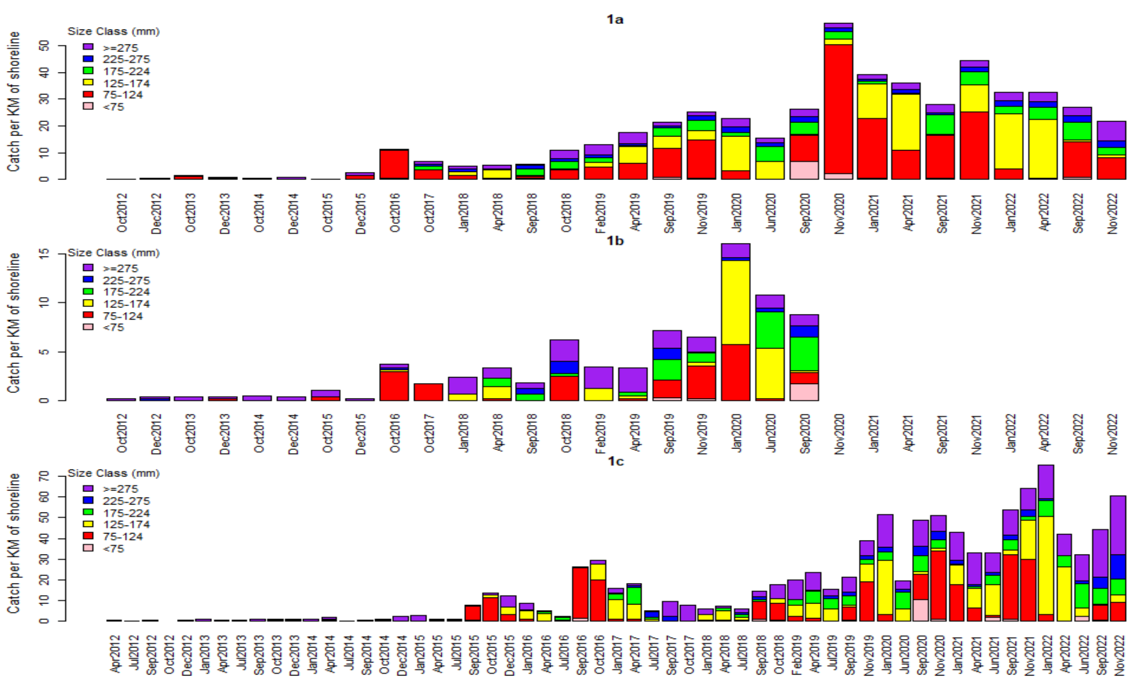

Figure 5. Brown trout catch per kilometer of shoreline over time in each subreach by size classes (colors). Preliminary data, do not cite.

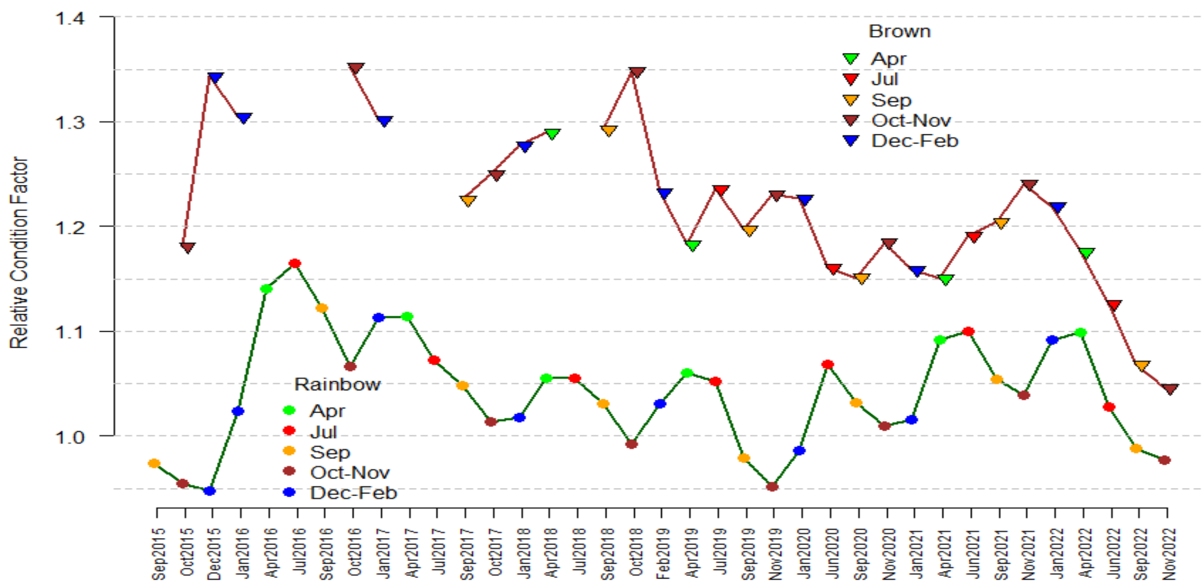

Figure 6. Relative condition factor for rainbow trout (circular symbol) and brown trout (diamond symbol) from electrofishing data collected in Glen Canyon between September 2015 and November 2022 for fish with a fork length of 275 mm or greater (April 2020 was cancelled due to COVID, no data). Points show the median value and error bars show 80% credible interval. Note that relative condition factor for brown trout is calculated using the equation for rainbow trout, for comparison purposes. Preliminary data, do not cite.

Reproductive Condition Research

Condition factor of rainbow trout in the fall is a good predictor of an index of sexual maturation rates the following winter and spring (Yard and Korman, 2020; Crossman and others, 2022). Condition factor is higher when growth is higher, potentially leading in turn to an increase in the proportion of trout that reach sexual maturity and spawn. 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 manipulated. This approach is known to lead to a substantial bias in sex ratios (i.e., males express gametes more readily than females), and it is the uncertainty of whether or not the percentage of males or females expressing gametes each year is proportional to the actual percentage of adults that spawn and contribute to recruitment.

In 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 results found that some of the larger male trout that would be expected to be reproductive are not, and overall, a surprisingly large proportion of adult fish are not reproductive. 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 high levels of competition. 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 reproductive work started in the 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 and further expanding the application of ultrasonography to understand the accuracy in assigning reproductive condition to the spawning population of each species.

Preliminary results show that based on size, like rainbow trout, a number of large brown trout that should be reproductive are not, a result which could be related to the declining condition in the population in recent years (Figure 6). Application of ultrasonography has been extremely successful with > 99% of trout > 275 mm scanned (n=1,116) on the November 2022 trip and assigned to a reproductive condition (specific reproductive stage for females). From the preliminary ultrasound data, rates of atresia appear to be high in rainbow trout in fall 2022. Work to compare the population reproductive structure between the two species and finalize a protocol for application of ultrasonography will be completed in 2023.

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). In 2022 we continued monitoring YOY trout populations in Marble Canyon and at 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 other factors like nutrients that influence upstream trout populations.

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

The Brown Trout Early Life Stage Survey (BTELSS) objectives are to: 1) understand early life stage vital rates for YOY brown trout in Glen Canyon, 2) assess hatch and swim-up dates to identify when brown trout are likely to be emerging from gravel redds, and 3) identify habitat preferences for low angle (cobble bars, vegetated sandbars, debris fans) versus high angle (talus) nearshore habitat to understand stranding vulnerability to experimental flows.

The BTELSS project was implemented as part of Project Elements H.3 and O.6 in the FY 2021-23 TWP. In 2021, we collected data to evaluate the effect of the Spring Disturbance Flow on early stages of brown trout, while 2022 served as a reference year. No additional data will be collected in 2023. From January 5 through May 12, 2022, we conducted six BTELSS trips spaced approximately 3-4 weeks apart.

In total, we captured 1,635 fish, of which 98.5% were YOY or age-1 trout (rainbow trout [n=941, 57.9%], brown trout [n=341, 21.0% of catch], unknown YOY trout [n=329, 20.3%]), and green sunfish [n=24, 1.5%]. We notably captured more green sunfish in 2022 than 2021 (n=5). Of the identifiable trout species in 2022, 27% were brown trout and 73% were rainbow trout. A large portion of the YOY trout in 2021 and 2022 were not field-identifiable (i.e., too small to distinguish in the field or had morphological characteristics of both species), so we sent those specimens to the American Southwest Ichthyological Researchers (ASIR) for positive identification and to develop a field key. In 2021, 252 of 342 specimens could be identified; 90 specimens were too degraded to assign species status.

All specimens were identified as rainbow trout; no YOY brown trout were identified in 2021. The 2021 results were available mid-field season in 2022, so we modified our sampling design in the last three trips to use different methods of capture (e.g., minnow traps - baited and unbaited - light traps, seines), sampling times (day and night), and different field locations (including backwaters) to further examine habitats that may be utilized by YOY brown trout in Glen Canyon. Of the 329 unidentified YOY trout in 2022, 16 specimens were identified as brown trout. YOY brown trout were only captured in the last two trips of the year (March 30-April 1, May 10-12, 2022), with most captures on cobble bars near -4.1 and -10.8 RM.

We sent 28 YOY or age-1 brown trout collected between 2016-2022 to ASIR for age determination and back-calculation of hatch dates (Figure 1a). Specimens ranged from 38-108 days post-hatch, with hatch dates ranging from January 30 to April 13. The embryos in this data set incubated for 45-53 days prior to hatching, indicating brown trout have a protracted spawning season that spans fall to early spring. Median hatch date was March 13, with the majority of brown trout hatching in the second week of March (Figure 1b). Preliminary results indicate a strong positive relationship (r = 0.939, P < 0.0001) between otolith age and standard length (mm) of fish, with a rapid rate of growth from 0.42 mm/d to 0.64 mm/d.

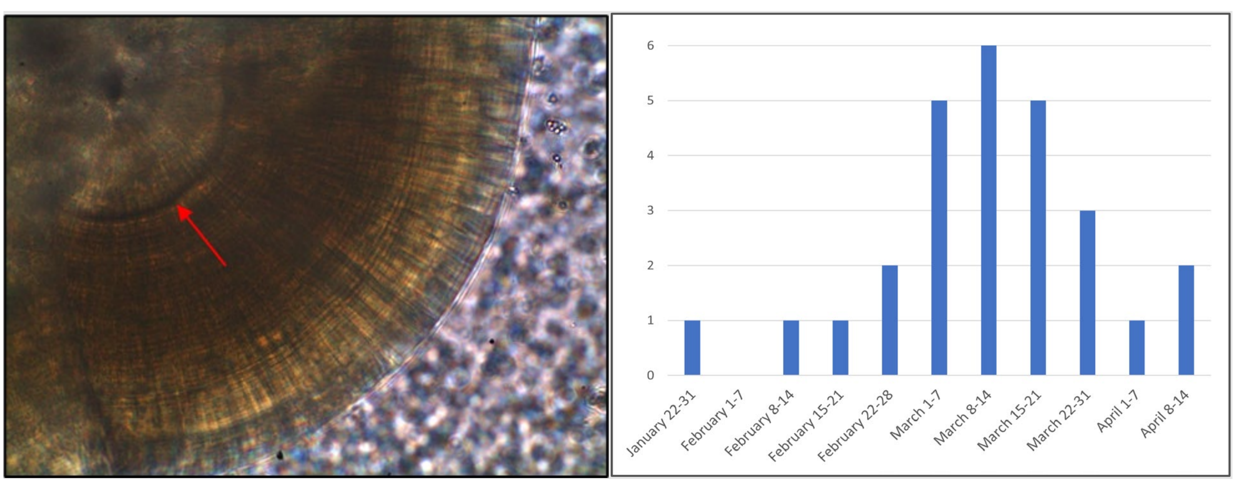

Figure 1. a) Sagittal otolith of a brown trout at 200x magnification. The red arrow indicates the hatch check. Age counts are determined by counting increments between the hatch check and the edge of the otolith. b) Hatch date distribution by week for YOY or age-1 brown trout in the Colorado River (Lees Ferry) captured between 2016-2022.

Element H.4. Salmonid Modeling

Science Questions/Hypotheses Addressed

The goal of Element H.4 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 is progressing but has been slowed by the requests to divert staff attention to smallmouth bass issues and understaffing, included the loss of the principal investigator of Project H (Kimberly Dibble), who left for a different job. In 2022, we collaborated with National Park Service colleagues to finish two manuscripts that address brown trout movement in response to the use of a weir in Bright Angel creek and fall HFEs (Healy and others, 2022) and simulate potential response of brown trout to different management and climate change scenarios (Healy and others, 2022). In 2022, two modeling manuscripts focused on rainbow trout dynamics were also accepted for publication. The first manuscript estimated the impacts of both fall high-flow events (HFEs) and bug flows on rainbow trout growth and contrasted the effects of sizes of these designer flows with the expected impacts of declining reservoir levels (Korman and others, 2022). 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). We have also made progress in modeling rainbow trout movement from an integrated model and plan to develop and submit a manuscript on this subject in 2023.

Results from the rainbow trout and brown trout models were reported at the January 2023 reporting meeting as usual but were not available in time for this written report.

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Project H Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$181,222	$11,700	$25,566	$148,000	$0	$31,371	**$397,859**
Actual Spent	$123,423	$5,874	$68,077	$152,685	$0	$28,909	**$378,968**
(Over)/Under Budget	**$57,799**	**$5,826**	**($42,511)**	**($4,685)**	**$0**	**$2,462**	**$18,891**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$18,891**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Underspent in Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is due to change in funding mechanism for a cooperator from a Cooperative Agreement to a contract.
-Overspent amount in Cooperative Agreement is additional funds sent to USFWS for eDNA analysis.

Project H Deliverables: Salmonid Research and Monitoring

Journal Articles:

Crossman, J.A., Webb, M.A.H., Korman, J., and Yard, M.D., 2022, Population reproductive structure of rainbow trout determined by histology and advancing methods to assign sex and assess spawning capability: Transactions of the American Fisheries Society, v. 151, no. 4, p. 422-440, https://doi.org/10.1002/tafs.10356.

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, online, https://doi.org/10.1139/cjfas-2022-0231.

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USGS Reports:

Giardina, M.A., Korman, J., Yard, M., Wright, S., Kaplinski, M., and Bennett, G., *in final edits with the USGS Science Publishing Network*, A literature review and hypsometric analysis to support decisions on trout management flows on the Colorado River downstream from Glen Canyon Dam: U.S. Geological Survey Open-File Report.

USGS Data Releases:

Yackulic, C.B., Yard, M., Korman, J., Rogowski, D., Healy, B.D., Schelly, R.C., Omana-Smith, E., and Nelson, C., 2022, Brown trout movement data in Glen and Grand canyons, Arizona, USA: U.S. Geological Survey data release, https://doi.org/10.5066/P96NII4B.

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

Project Lead	David Ward	**Principal Investigator(s)** (PI)	David Ward, USGS, GCMRC David Rogowski, AZGFD Kirk Young, USFWS Kimberly Dibble, NPS (formerly with USGS, GCMRC) Charles Yackulic, USGS, GCMRC
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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 fish as well as identifying new invasive aquatic species (system wide native fish and aquatic invasive species monitoring). This project also provides detection capability for new warm-water invasive fish, 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 fish). Nonnative fish 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 fish in the CRe early improves the likelihood that a successful rapid containment/eradication response can be accomplished before negative impacts on endangered populations occur (Martinez and others, 2014). In addition, this project quantifies the potential negative impacts of nonnative fish 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 fish in replicated laboratory trials (assess the risks warm-water nonnative fish pose to native fish).

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 fish 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 abundance and distribution of native and nonnative fish throughout Grand Canyon. Trends in CPUE over time for system wide native and nonnative fish 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 would indicate a significant trend. 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.

Element I.2. is focused on improving early detection of warm-water invasive fish. 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 is conducting an eDNA project. The objective of the eDNA project is to detect rare native and nonnative species by filtering DNA from the water. Fish shed scales, mucous, and other products are shed into the water, allowing researchers to collect that DNA 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 fish will be used to direct future monitoring efforts or emergency responses as needed.

The goal for Element I.3 of this project is to evaluate impacts of invasive nonnative warm-water fish on humpback chub (*Gila cypha*) in both laboratory and field settings. Our objective is to quantify the relative risks that each warm-water predator poses to native fish. The risks of predation on humpback chub by existing predators such as channel catfish (*Ictalurus punctatus*), common carp (*Cyprinus carpio*), and green sunfish (*Lepomis cyanellus*) need to be quantified. The potential impact of smallmouth bass *(Micropterus dolomieu)*, which are not yet established in the CRe but are likely to become established, have also not been quantified. Our goal is to evaluate the relative predation vulnerability of humpback chub to these predatory warm-water species using methods similar to those employed for past trials with rainbow and brown trout (Ward and Morton-Starner, 2015). Standardized methods allow comparison of relative predation risks. These data will allow managers to understand which warm-water invasive fish are the most detrimental to humpback chub populations so that management efforts can be focused on those species that are the most problematic.

Science Questions Addressed & Results

Project Elements

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

Science Question

- What is the species composition, relative abundance, longitudinal distribution, and population trends of the fish assemblage inhabiting the CRe?

Results

AZGFD completed two mainstem sampling trips in 2022 to continue our long-term monitoring and describe the relative abundance and distribution of native and nonnative fish throughout the Colorado River in Grand Canyon. On the spring trip (April 1-14, RM 0 - 281), we captured 1,113 fish at 166 electrofishing sites, 2802 fish in 166 baited hoop nets, and 22 fish with 13 evenings of angling. Turbidity during the spring trip was high downstream of the Little Colorado River, so we reduced the number of electrofishing sites and increased the number of hoop nets set downstream of the Little Colorado River. During the autumn sampling trip (Nov 1-4) we sampled upstream of Pearce Ferry Rapid (RM 271 - 281.5). Due to the low water, shifting sandbars, and turbidity, electrofishing at night was deemed too dangerous during our autumn trip, thus we only electrofished one night. We captured 13 fish at 14 electrofishing sites, 483 fish in 56 hoop net sets, and no fish at three angling sites.

Over the 23 years of AZGFD monitoring, relative abundance of most nonnative species has decreased, and abundance of most native species has increased. This year, we observed similar fish distribution patterns to recent years (e.g., 2016-present), with nonnative rainbow trout comprising most (89.4%) of the electrofishing catch in Marble Canyon, and native fish comprising most of the catch (98.7%) downstream of the Little Colorado River confluence. Rainbow trout *(Oncorhynchus mykiss)* and flannelmouth sucker (*Catostomous latippinis*) were the most captured species during our spring monitoring this year (44.9 and 43.8% of electrofishing catch, respectively). Rainbow trout appeared to compromise a greater percentage of the fish assemblage captured by electrofishing this year because of reduced electrofishing downstream of the Little Colorado River in response to high turbidity.

Results from hoop nets sampling in 2023 reveal a similar number of fish over the past three years (Figure 1). Flannelmouth sucker were the most common species (85.9%) captured in hoop nets in spring of 2022, and the only native fish captured throughout the entire canyon. This year (2022), we observed a higher CPUE of flannelmouth sucker in reaches of Marble Canyon as well as in Glen Canyon than in previous years. In our autumn sampling for the first time, humpback chub were the most common species captured in hoop nets, comprising 62.1% of our catch. Only 20% of humpback chub captured in the autumn were previously tagged, compared to 34% during our spring monitoring.

Each gear type has certain biases and targets different species. Angling targets channel catfish, and in the past has been a productive method of capturing numerous channel catfish. In recent years we rarely captured channel catfish angling (0-1), and this year was no exception; we didn’t catch any. This year humpback chub were the most common species captured angling (n=17). We also captured four rainbow trout, and one common carp.

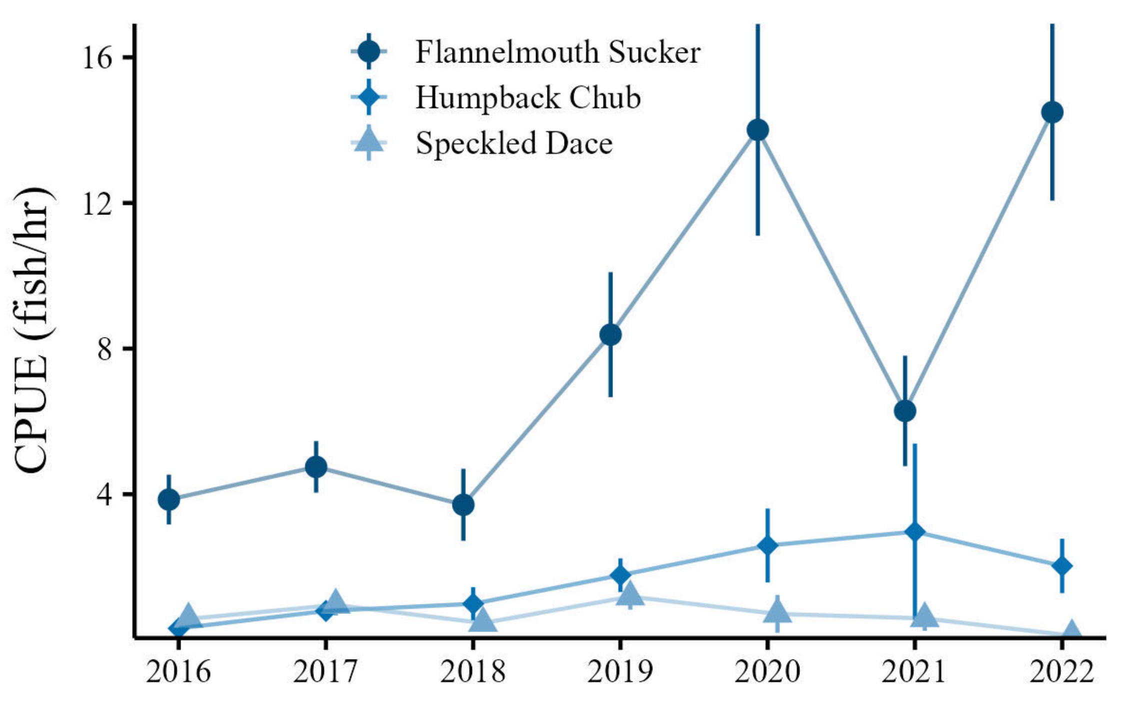

Figure 1. Catch-per-unit effort (fish/net night) with 95% CI of native fish from baited hoop nets from AZGFD spring long-term monitoring of the Colorado River.

Rare nonnatives captured in the spring sampling included brown trout (n=17 fish captured), common carp (n=4), fathead minnow (n=5), yellow bullhead (n=4), green sunfish (n=1), red shiner (n=1), and striped bass (n=1). During autumn monitoring we captured four crayfish and one fathead minnow.

An additional question of interest in recent years has been "Is Pearce Ferry Rapid an impediment to fish movement?" Catch data suggest that this rapid became much larger and changed hydraulically in approximately 2008 and continues to be dynamic. It may limit movement of nonnative fish (e.g., common carp, channel catfish) between Lake Mead and the Colorado River in Grand Canyon but could also impede native fish movement. To investigate this question, AZGFD installed Passive Integrated Transponder (PIT) tag antennas at the rapid and samples fish both upstream and downstream of the rapid (work at rapid and downstream of rapid is not funded by GCDAMP). On our Grand Canyon trips, we tagged all flannelmouth sucker > 150 mm TL caught downstream of RM 270 to have more tagged fish near the Pearce Ferry Rapid PIT antenna array and gain a better understanding of how this rapid affects fish movement. Preliminary data, based on the differences in fish assemblage upstream and downstream of the rapid, and PIT tag antenna data suggest that the rapid is a hindrance to fish movement upstream.

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

Science Questions

- What warm-water nonnative fish are present in the CRe and how can we improve our ability to detect new invasions of warm-water nonnative fish before they become established?
- Can new eDNA tools be used to effectively collect this information?

Results

AZGFD conducted spring (March 17-18) and summer (July 14-15) targeted monitoring of invasive warm-water species in Glen Canyon in areas where rare nonnatives have been caught before. These areas include right up next to the dam, and in warmer water areas such as spring inflows, sloughs, and backwaters. In the fall of 2022, these efforts captured 75 bluegills *(Lepomis macrochirus)*, 15 green sunfish, two green sunfish/bluegill hybrids, 2 common carp, and 11 smallmouth bass. The largest smallmouth bass captured was 205 mm TL; all the rest were YOY and less than 116 mm TL. Smallmouth bass were also captured in eight of the 40 standardized monitoring sites along with black crappies *(Pomoxis nigromaculatus*; 90, 91, 99 mm TL), which were also captured at standardized monitoring sites (-12.55L, -7.93R, -5.07L, respectively). More smallmouth bass were caught in normal standardized monitoring (14) than in focused sampling (11), indicating that AZGFD standardized monitoring is sufficient to detect this species at current abundances within Glen Canyon.

Two environmental DNA sampling trips were conducted in 2022, with one occurring upstream from Lees Ferry on July 15 and one occurring downstream of Lees Ferry from June 1-9 (See FY 2021-23 work plan for detailed sampling methods). High turbidity during much of the trip made filtering water very time consuming. Samples have all been sent to the USDA Forest Service Rocky Mountain Research Station for processing and analysis.

Element I.3. Assess the Risks Warm-Water Nonnative Fish Pose to Native Fish

Science Question

- What are the current impacts of the existing population of introduced channel catfish on juvenile humpback chub in the Little Colorado River and are those impacts more or less of a threat than predation by other introduced fish?

Results

In 2022, field efforts continued to focus on marking channel catfish within the Little Colorado River. We completed five angling trips within the lower 13 km of the Little Colorado River (May - June). Only 22 channel catfish were caught and tagged with Passive Integrated Transponder (PIT) tags in 171 hours of angling effort (0.13 fish/hour). This represents a four-fold decline in catch rates compared to the previous two years of effort. Channel catfish were widely distributed throughout the lower 13 km of the Little Colorado River and typically aggregated in deeper pools with large boulders. This year the population was dominated by large adult, male catfish with the average size being 516 mm TL (range = 335-710 mm Total Length [TL], Figure 2).

Although rarely caught with other sampling methods, adult channel catfish are very susceptible to angling with earthworms. Only 3 catfish which were tagged in previous years were recaptured. The lack of females, and the few large males that were caught may indicate that smaller female channel catfish exited the Little Colorado River or died between 2021 and 2022. Movement information from the three recaptured fish this year indicates they are resident fish with most recaptures occurring within the same pool complex. No mark-recapture population estimate (Lincoln-Petersen method) was able to be calculated in 2022 because of the low number of recaptures and the apparent exit of catfish from the Little Colorado River, which violates closure assumptions. Warmer mainstem water temperatures may have resulted in channel catfish remaining in or moving into the mainstem Colorado River. Incidence of piscivory, based on gastric lavage, continues to be relatively high. In 2021, 14.5% of catfish had eaten fish within the 24-hour period prior to being caught. In 2022, 27.3% (6 out of 22 fish) of catfish had eaten fish within the 24-hour period prior to being caught. This relatively high incidence of piscivory may indicate the potential for large negative impacts on all of the native fish through predation.

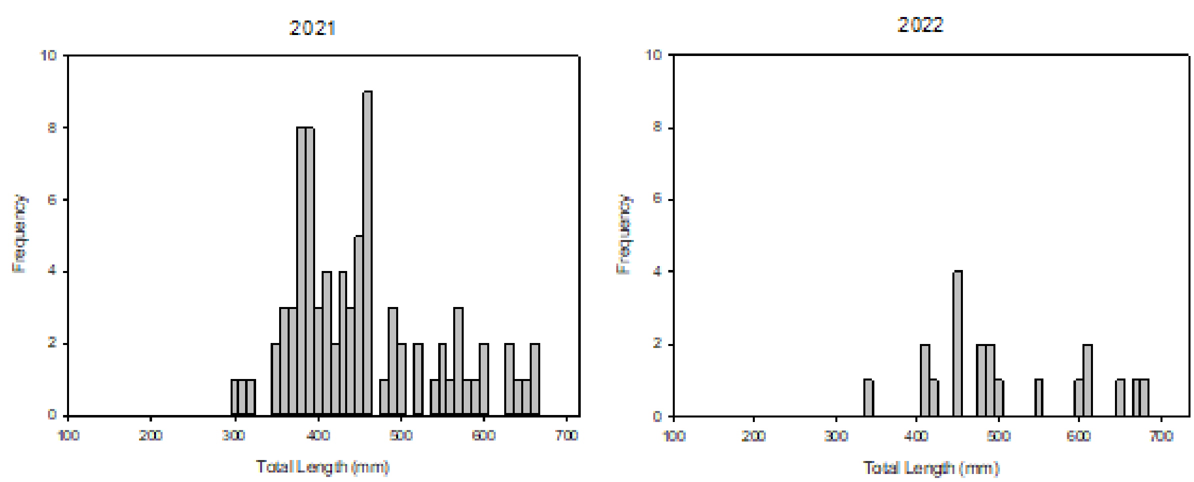

Figure 2. Length frequency histogram for channel catfish angled from the Little Colorado River in 2021 and 2022 (with similar effort) indicating reduced numbers and fewer smaller sized fish are present in the Little Colorado River. Preliminary results, do not cite.

In 2022, laboratory evaluations of predation risk were focused on the potential impacts of channel catfish on juvenile humpback chub and the risks that common carp pose to survival of humpback chub eggs. For channel catfish, laboratory predation trials focused on the effects of turbidity on predation vulnerability of native fish. In replicated laboratory trials conducted in clear water, flannelmouth and razorback sucker *(Xyrauchen texanus)* were found to be 50-90% more vulnerable to channel catfish predation than humpback chub or bonytail chub *(Gila elegans)*. When turbidity was increased (250-500 nephelometric turbidity units, NTU) predation vulnerability to channel catfish also increased, and species-specific differences in predation vulnerability became less apparent, indicating that periods of high turbidity are likely when channel catfish are the most detrimental to native fish within the Little Colorado River.

To evaluate the effects of common carp on humpback chub eggs and larvae, seven additional replicate trials were conducted with common carp in larger 1,000-gallon tanks with cobble substrates (tank size increased by a factor of 5, compared to trials conducted in 2020). Tank size was increased to verify that results obtained in 2020 were not just related to small tank size. Two common carp adults were allowed access to newly fertilized humpback chub eggs for a 24-hr period in these larger tanks. Carp predation on eggs resulted in an average 90% decrease in humpback chub eggs that survived to swim-up, compared to control tanks with no carp present. This effect size is similar to a 2020 experiment, which showed a 96% decrease in egg survival in common carp tanks, and demonstrates that common carp are likely to pose a significant risk to the survival of humpback chub eggs through predation in the Little Colorado River. Adult common carp were also found to be effective predators on juvenile chub and suckers. Additional 24-hr laboratory predation trials were conducted using captive reared juvenile bonytail (22-70 mm TL), humpback chub (21-49 mm TL), and razorback sucker (47-98 mm TL) as prey. Chubs and suckers both experienced unexpectedly high predation mortality, with the smallest sizes (fish < 80 mm TL) being most vulnerable with up to 50% predation mortality occurring in overnight trials conducted in turbid water (500 NTU, figure 3). These results demonstrate that common carp are not just a threat to eggs and larval native fish, but also to juveniles. This information gives context about potential management actions designed to conserve Colorado River native fish. Additional carp-focused management actions within the Little Colorado River may be warranted to conserve imperiled native fish.

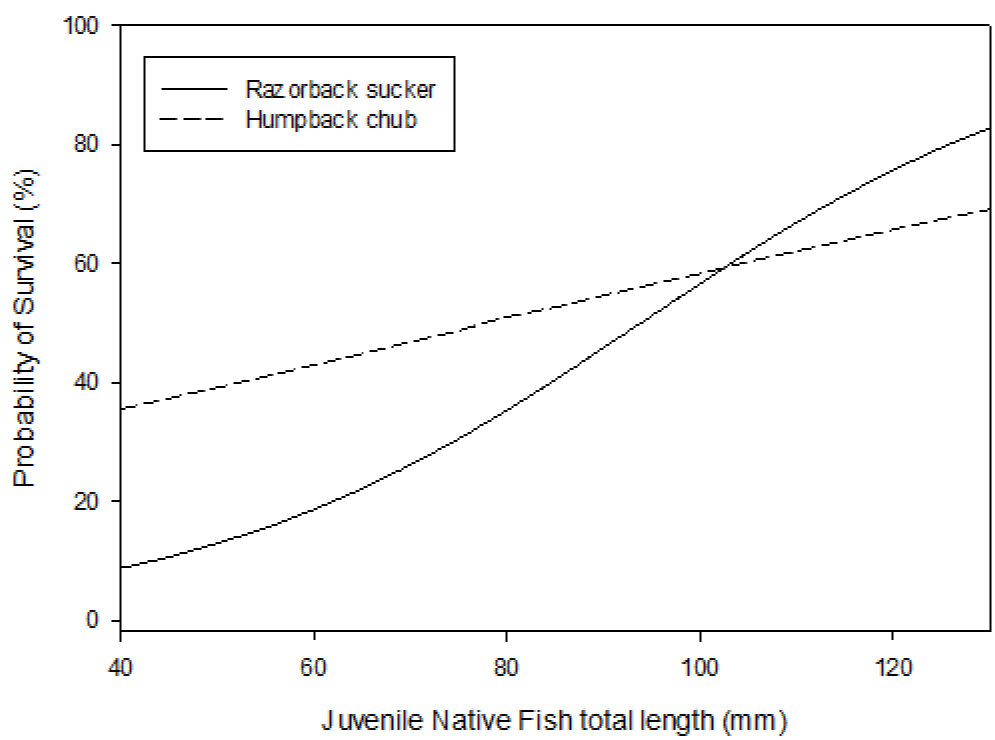

Figure 3. Probability that juvenile razorback sucker and humpback chub will survive predation by adult common carp in turbid water (500 NTU) in replicate overnight trials conducted in the laboratory. Preliminary results, do not cite.

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Project I Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$233,790	$0	$12,100	$273,110	$0	$38,502	**$557,502**
Actual Spent	$272,402	$1,724	$18,141	$273,110	$0	$44,218	**$609,595**
(Over)/Under Budget	**($38,612)**	**($1,724)**	**($6,041)**	**$0**	**$0**	**($5,716)**	**($52,093)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($52,093)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Overspent Salaries is due to assignment of project staff reassigned back to the project to ensure completion of all project tasks outlined in the workplan.
-Overspent funds in travel and training is due to travel and training completed in FY22 that was rescheduled from FY21.
-Overspent funds in Operating Expenses is for purchases of necessary lab equipment and field supplies.

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

Presentations:

Frye, E., and Ward D., 2022, Common carp, uncommon predator—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Frye, E., and Ward D., 2022, Green sunfish, aquatic gremlins of the southwest—poster presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Rogowski, R., 2022, Back to the future, warm-water fish in the Grand Canyon—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Ward D., and Frye, E., 2022, Oxygen manipulation for fisheries management—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Project J: Socioeconomic Research in the Colorado River Ecosystem

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Goals and Objectives

In the GCDAMP TWP FY 2021-23 (U.S. Department of the Interior, 2020), Project J is integrating economic information with data from long-term and ongoing physical and biological monitoring and research studies led by GCMRC. This integration will lead 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 incentivized harvest program and recreational preferences for trip attributes (e.g., flows) that allow for inference into how recreational economic values are influenced by GCD operations.

Project J's primary goal in the GCDAMP TWP FY 2021-23 is to address the humpback chub *(Gila cypha)*, hydropower and energy, and sediment or recreational experience LTEMP FEIS resource goals. This goal is accomplished by addressing the LTEMP Record Of Decision (U.S. Department of Interior, 2016a; U.S. Department of Interior, 2016b) 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 Questions

- 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) and are also able to maintain or improve the value of hydropower generation at GCD?

Results

- Preliminary results indicate 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 Interior, 2016b). See the FY 2021 GCMRC Annual Report (U.S. Geological Survey, 2021) for additional details related to preliminary results.

In FY 2022, GCMRC and cooperators began 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). The model 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 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 Questions

- 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 particular program was unsuccessful at drawing additional fishing effort (in daily trips) into the fishery, and had mixed results on the number of brown trout that anglers caught and retained.

The primary objective of Project Element J.2 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 2022, 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 2023. In cooperation with AZGFD (see Project H), in FY 2022 GCMRC also led approximately 50 days of angler surveys at Lees Ferry.

These angler surveys provide detailed information related to the brown trout incentivized harvest program that is important in the first year of the program to determine participation rates under various incentive structures. The angler surveys also 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 initiated the required Office of Management and Budget review as part of the Paperwork Reduction Act in early calendar year 2022. It is anticipated that the survey will be approved in early calendar year 2023 and implemented in the same year.

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 1).

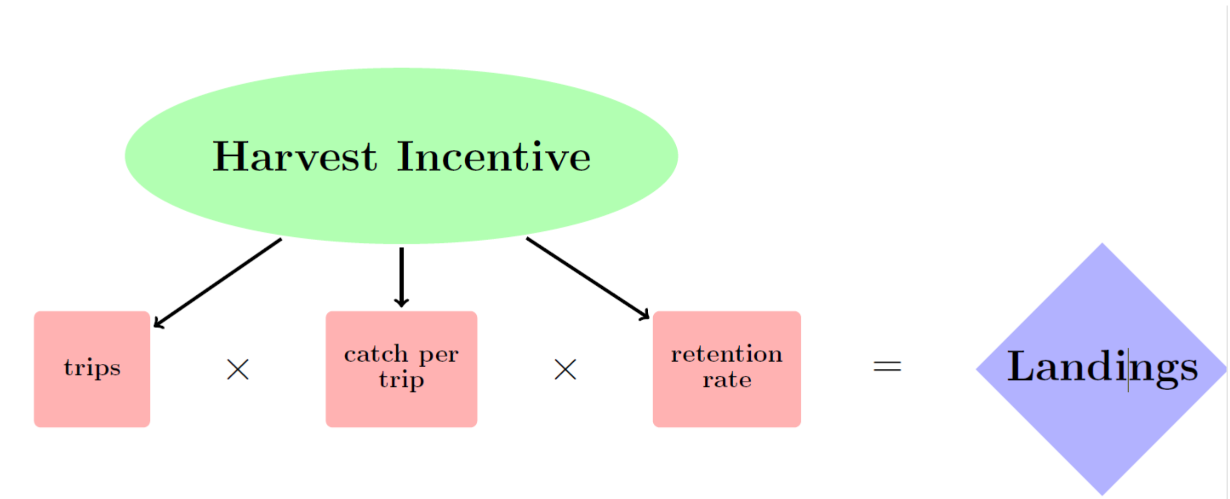

Figure 1. The factors over which a program incentive may increase brown trout harvests.

We use daily, angler-level data on fishing behavior and outcomes from the Arizona Game and Fish Department Lees Ferry creel survey (January 2016 - May 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 1). 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. 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.

Our preliminary results suggest that the Lees Ferry Incentivized Harvest Program failed to bring additional angling effort (i.e., daily trips) into the fishery, likely due to how remote and costly it is to access the fishery. Interestingly, the program seems to have had an unambiguously negative impact on catch per trip for both rainbow and brown trout. With no increase in trips due to the program, this suggests that anglers changed their targeting behavior (i.e., where they fished, what gear they used, etc.) in response to the program treatment, but either crowded out each other's efforts or lacked Lees Ferry-specific knowledge on where and how best to target brown trout. 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 catch rates. We also find mixed results on whether or not the program had a positive or negative effect on brown trout retention rates. Because retention rates are a fraction, and thus bounded at one, it may be the case that these ambiguous results reflect minimal ability for the program to increase retention rates in the participating population. We plan to explore this hypothesis further and also assess how retention rates may have changed according to angler type to identify potential mechanisms driving these results.

Element J.3. Recreation Monitoring and Research

The objective of Project Element J.3 is to further refine our understanding of recreational preferences for specific flow attributes as controlled by operations at GCD and within the flow parameters of the LTEMP ROD (U.S. Department of Interior, 2016b). No funded research was conducted in FY 2022.

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Project J Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$124,588	$3,000	$1,500	$45,500	$0	$17,276	**$191,864**
Actual Spent	$95,952	$5,874	$9,782	$69,000	$0	$15,827	**$196,435**
(Over)/Under Budget	**$28,636**	**($2,874)**	**($8,282)**	**($23,500)**	**$0**	**$1,449**	**($4,571)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($4,571)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 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 an international workshop organized by The Amazon Dams Network in Brazil.
- 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.S., and Bain, D.M., 2021, Identifying the total economic value of hydropower and implications for adaptive management of rivers—Operating restrictions of hydroelectric plants and their impacts on the operation of the Brazilian electric system—virtual presentation: XXIV Brazilian Symposium on Water Resources, November 2022.

Bair, L.S., 2021, Adaptive management and cultural ecosystem services—virtual presentation: ACES: A Community on Ecosystem Services conference, December 2022.

Bair, L.S. and Neher, C., 2022, Recreational anglers' preferences for flow attributes—Taking advantage of a designer flow to validate novel scenarios—virtual presentation: The International Institute of Fisheries Economics and Trade, July 18-22, Vigo, Spain.

Bair, L.S., 2022, Consideration of plural values in integrated assessments—presentation: AGU Chapman Conference on Solving Water Availability Challenges through an Interdisciplinary Framework, September 12-16, Golden, Colorado.

Journal Articles:

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

Hoelting, K., Morse, J.M., Gould, R., Martinez, D.E., Hauptfeld, R.S., Cravens, A.E., Breslow, S., Bair, L.S., Schuster, R.M., and Gavin, M.C., 2022, Opportunities for improved consideration of cultural benefits in environmental decision-making: SocArXiv, p. 1-42, https://doi.org/10.31235/osf.io/dpbe3.

Jungers, B., Abbott, J.K., Bair, L.S., *in prep*, Program evaluation of the Lees Ferry brown trout incentivized harvest program.

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
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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 now 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 FY 2021-2023 Triennial Work Plan (TWP) —Geospatial Data Analysis, Geospatial Data Management, and Access to Geospatial Data Holdings and Online Data Resources. Many aspects of the efforts put forth through this project often overlap from one element to another and can be discussed in all three of these elements. The approach Project K has employed for these project elements has had two underlying threads – 1) support the overall GCMRC 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 Project Element K.1 is designed to support research and monitoring projects from the FY 2021-2023 TWP 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 GCMRC-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, 2020). Additionally, this project is responsible for handling data calls pertaining to a wide array of GCMRC's data resources every year. In FY 2022, Project K expanded 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. Additional relational database work is also addressed under Project Element K.2.

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 GCMRC'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 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. More on the online availability of Tableau data visualizations is discussed in Project Element K.3.

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 occasionally oversight of SBSC Information Technology 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 GCMRC in the maintenance and further development of open-source databases, specifically building upon the work in fiscal year 2021 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 seven database endpoints, each uniquely configured to optimize storage and retrieval of either tabular-centric or geospatial-centric data resources for GCMRC. Most notably is GCMRC's Fish Monitoring Database, which has received a great deal of attention toward improving both how the database functions to the workflows employed to import field collected data to 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 the data stewards of this information.

Through improved coordination efforts 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. We now can now view, in real-time, the Fish Monitoring Database trip status through a widely available data visualization (Figure 1) that shows the Month, Trip ID, Total Samples per trip, and Total Specimens per trip. This is a draft visualization 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.

Also in FY 2022, a large amount of effort was put toward finalizing the Lake Powell Water-Quality database. This effort involved close coordination with the Lake Powell water-quality principal investigator (Deemer) and a significant amount of time to fix issues with the data entry of certain water-quality parameters and refine the QA/QC process for sampling data. This work has led to a data release and a peer-reviewed journal article on the Lake Powell Water-Quality database and established workflows that are now being used (Deemer and others, 2023).

Figure 1. View of Tableau data visualization of fish monitoring database showing the trip data entry status along with number of total samples and total specimens by species collected for each trip.

Management of Cloud Environment Usage for Science Project Support

Project K has led GCMRC in expanding the role of data management to include a hybird-cloud approach for future data needs and, more specifically, project staff actively maintain 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:

1. Further develop the GCMRC's capacity for working in and building applications in AWS.
2. 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.

3. Build more proficiency among science project staff and Project K staff to work with 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

Project Element K.3 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 GCMRC's data resources online becomes more difficult. 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.

Project K continued to perform all the administration, installation, system upgrades, and content expansion made available through an online portal (Grand Canyon Geospatial Portal, https://grandcanyon.usgs.gov/portal/home/) as well as sharing many of these data services through the ESRI ArcGIS Online (https://www.arcgis.com/) cloud platform. 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.

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

We have expanded GCMRC's use of the USGS' Cloud Hosting Solutions (CHS) Sensor Processing Framework and provided unparalleled opportunities for accessing important GCMRC data resources. In FY 2022, 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 performing this type of work.

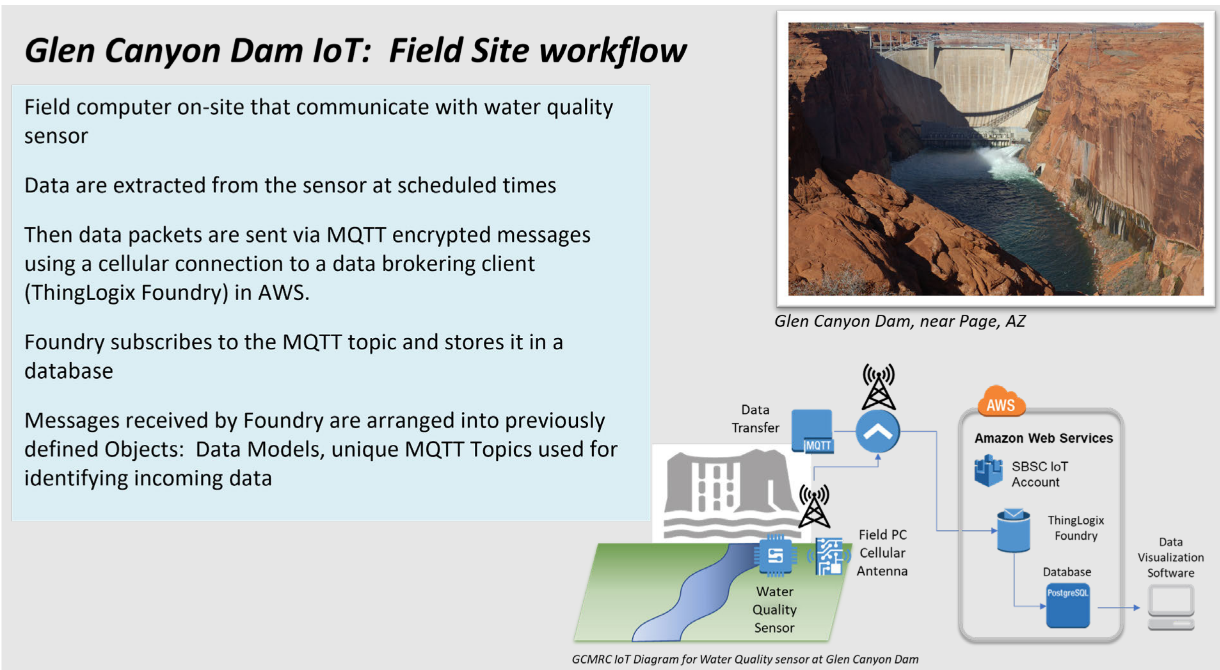

Figure 2. Slide from a presentation given on the advances made in GCMRC's data telemetry using modern Internet of Things technologies. The schematic illustrates the technological stack employed and the workflow used to make the data available online in near real-time.

Continued coordination led by Project K has allowed GCMRC to leverage USGS resources, including continued involvement with Cloud Hosting Solutions and the CHS Sensor Cloud Processing Framework, the Center for Data Integration, and the Actionable and Strategic Integrated Science and Technology (ASIST) project. The ASIST project is the next generation of the previous Earth Monitoring, Analysis, and Prediction (EarthMAP) initiative and associated Colorado River Basin pilot project that was instituted to improve data workflows, modeling, and prediction for the Colorado River Basin. In FY 2022, Project K staff presented on the efforts to modernize data collection along the Colorado River as a part of the ASIST session at the Colorado Plateau Biennial Conference (Figure 2). The list of data telemetry sites includes 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 3).

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 from 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 for further consumption.

Figure 3. Viewing of online data visualization of Glen Canyon Dam water-quality information.These data have been published as a versioned data release (Andrews and Deemer, 2022) and available to GCMRC and the Bureau of Reclamation since 2022. The data visualization will be made publicly available in 2023. Preliminary, do not cite.

References

Andrews, C.M., and Deemer, B.R., 2022, Limnology data from Lake Powell, desert southwest USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZIKVYW.

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, online, https://doi.org/10.1002/lol2.10310.

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/.

Project K Budget

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$372,175	$4,970	$3,400	$0	$0	$46,906	**$427,451**
Actual Spent	$275,035	$0	$11,342	$0	$0	$35,299	**$321,676**
(Over)/Under Budget	**$97,140**	**$4,970**	**($7,942)**	**$0**	**$0**	**$11,607**	**$105,775**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$105,775**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Unspent Salaries is due to staff turnover in FY22 and HR-delays in hiring of a Database Administrator and a Geographer which will occur in FY23.
- Unspent Travel & Training money due to travel restrictions imposed by COVID-19 pandemic.
-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

Note: listed here are products that include Project K staff as authors; however, the work plan and budget for some products reside in other science projects.

Presentations:

Gushue, T.M., Andrews, C.M., and Thomas, J.E., 2022, Modernizing sensor data workflows to leverage Internet of Things (IoT) and cloud-based technologies—presentation: USGS Community for Data Integration monthly meeting, May 2022.

Gushue, T.M., Thomas, J.E., 2022, Modernizing sensor data workflows to leverage Internet of Things (IoT) and cloud-based technologies—presentation: USGS Cloud Hosting Solutions customer user group meeting, August 2022.

Gushue, T.M., Thomas, J.E., and Andrews, C.M., 2022, Modernizing data telemetry efforts for important riparian resources in the Grand Canyon—abstract for 16th Biennial Conference for Science and Management on the Colorado Plateau and Southwest Region, September 12-15, 2022: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz.

Thomas, J.E., Gushue, T.M., Andrews, C.M., and Unema, J., 2022, Using NWIS data from multiple gauging stations to capture event based video—presentation: USGS Community for Data Integration 2023 Request for Proposals Lightning Presentations.

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, online, https://doi.org/10.1002/lol2.10310.

USGS Reports:

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., Gushue, T.M., Buscombe, D., and Kohl, K., 2022, Channel mapping of the Colorado River from Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona: U.S. Geological Survey Open-File Report 2022-1057, 20 p., https://doi.org/10.3133/ofr20221057.

USGS Data Releases:

Andrews, C.M., and Deemer, B.R., 2022, Limnology data from Lake Powell, desert southwest USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZIKVYW.

Kaplinski, M., Hazel, J.E. Jr, Grams, P.E., Gushue, T.M., Buscombe, D.D., and Kohl, K., 2022, Channel mapping Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona - Data: U.S. Geological Survey data release, https://doi.org/10.5066/P98GFP93.

Manuals:

Thomas, J.E., 2022, Little Colorado River humpback chub Pit Tag master controller IoT system—User and maintenance manual: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/little-colorado-river-mux-antenna/-/blob/main/Little_Colorado_River_Pit_Tag_Master_Controller_Manual_V1.pdf.

Thomas, J.E., 2022, Satellite remote relay design—User and maintenance manual, Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/blob/main/Satellite%20Relay%20System/Satellite_Remote_Reboot_Manual_V1.pdf.

Thomas, J.E., 2022, Taylor Woods IoT Datalogger—User and maintenance manual: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/taylor-woods-iot-data-loggers/-/blob/main/Taylor_Woods_IoT_Datalogger_Manual_V2.pdf.

Websites & Web Applications:

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

Web Content on ESRI ArcGIS Online:

- 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
- 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

Online Data Visualizations:

Gushue, T.M, and Thomas, J.E., 2021, Daily Water-Quality Data at Glen Canyon Dam—online data visualization: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, https://tableau.usgs.gov/t/InternalGuestAccess/views/WaterQualityatGlenCanyonDam/DailyWaterQualityDataatGlenCanyonDam?%3Aembed=y&%3AisGuestRedirectFromVizportal=y#1.

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

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

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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 processed in order to prepare them for publication in 2023.

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 were the basis for the 2016 Long-term Experimental and Management Plan (LTEMP) (U.S. Department of 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 2022 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 coming decades. For these reasons, this project is mission critical to successfully inform the GCDAMP on performance of the LTEMP ROD (U.S. Department of 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 2022 focus was to (Table 1): 1) conduct QA/QC of the data sets acquired by the contractor Fugro Geospatial, Inc. (Fugro) during the 2021 overflight, 2) implement final modifications to data, and 3) begin the USGS publication process for 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.

Fugro delivered draft image mosaic and DSM data sets to GCMRC during the first quarter (Q1) of FY 2022. GCMRC reviewed those data, requested revisions, and then during Q2 worked in coordination with the contractor to review and request further revisions to the data sets. In Q3, the contractor 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.

- Ortho Mosaic: Complete mosaic using error free flightlines; 20cm pixel resolution with four bands (Blue, Green, Red, Near-infrared). These data are sectioned based on USGS 7.5 quadrangle maps.

The project focus for FY 2022 was to conduct the quality assurance and quality control (QA/QC) at GCMRC. GCMRC reviewed each iteration of draft data sets for completion and requested edits to assure they meet the standards defined in the contract. We will extensively review the mosaic as this is a new deliverable from the contractor. When the project was initially developed, GCMRC project staff anticipated they would need to conduct image processing steps to fix issues associated with shadowing and topographic distortion in discrete locations throughout the data sets to prepare them for publication as USGS data sets. Project staff are currently working on this phase of the project, using 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 to complete an internal accuracy assessment of the registration of the image data and the vertical accuracy of the DSM and DEM data sets.

At the time of writing this report, the DSM and DEM data are in review for publication, and progress on the image mosaic data set is on track and those data are expected to be published in 2023 as planned. In 2023, final checks will be to compare the mosaic to past mosaic data sets (years 2002, 2009, 2013) to make sure that the data are acceptable to evaluating decadal trends in the Colorado River ecosystem. Once the checks for QA/QC and accuracy are completed GCRMC, scientists will begin working on derivative data products. These include water, sand, and vegetation maps.

Table 2. 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.

Fiscal Year	Quarter(s)	Activities
2021	1st	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
	2nd	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.
	3rd	Overflight mission Rim-level GPS base station operations River-level accuracy assessment and ground-truthing operations.
	4th	Monitor image processing performed by Fugro (contractor)
2022	1st	Data delivered to GCMRC QA/QC performed by GCMRC in coordination with vendor
	2nd	Final modifications to mosaic performed by GCMRC
	3rd & 4th	Begin publication process at GCMRC for finalized mosaic
2023	All	Image mosaic published by GCMRC Landcover classification maps produced by GCMRC remote sensing staff

Project L Budget

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$164,641	$0	$0	$80,596	$0	$22,712	**$267,949**
Actual Spent	$153,144	$2,286	$11,482	$80,596	$0	$22,992	**$270,501**
(Over)/Under Budget	**$11,497**	**($2,286)**	**($11,482)**	**$0**	**$0**	**($280)**	**($2,552)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($2,552)**
COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*							
FY22 Comments: -Underspent Salaries is due to staff turnover at the end of the fiscal year and change in mechanism for completing work. -Overspent Travel & Training was for travel for a cooperator to the bi-ennial conference. -Overspent in Operating Expenses is due to compensating contractors for data analysis.							

References

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

Project M: Leadership, Management, and Support

Project Lead	Mike Moran, Acting Chief	**Principal Investigator(s)** (PI)	Mike Moran, USGS, GCMRC (retired) Scott VanderKooi, USGS, SBSC
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Office	928-556-7289		

Goals and Objectives

During FY 2022, the budget for Project M included funding for leadership personnel including salaries, travel, and training for the Chief and Deputy Chief, part of the salary and travel for one program manager, and part of the salary for a data steward. 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 Department of Interior (DOI)-owned and GSA-leased vehicles that USGS Grand Canyon Monitoring and Research Center (GCMRC) uses for travel and field work. 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. GCMRC scientists participated in the three Partners in Science river trips conducted in FY 2022 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 and invertebrate ecology (Project F), the biology and ecology of native and nonnative fish including humpback chub (Projects G and I), and rainbow trout (Projects H).

Project M Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$690,221	$20,000	$178,000	$0	$0	$109,482	**$997,703**
Actual Spent	$535,988	$0	$194,321	$0	$0	$90,018	**$820,327**
(Over)/Under Budget	**$154,233**	**$20,000**	**($16,321)**	**$0**	**$0**	**$19,464**	**$177,376**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$177,376**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to staff turnover and HR delays in hiring the new GCMRC Chief.
- Underspent Travel & Training was due to travel restrictions and cancellations associated with COVID-19.
- Overspent funds in Operating Expenses is due to providing funds for shortfalls for project A and rising costs for vehicle maintenance and fuel.

Logistics Budget

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$269,502	$3,000	$1,074,767	$11,000	$0	$166,394	**$1,524,663**
Actual Spent	$216,046	$102	$1,237,597	$18,000	$0	$179,729	**$1,651,474**
(Over)/Under Budget	**$53,456**	**$2,898**	**($162,830)**	**($7,000)**	**$0**	**($13,335)**	**($126,811)**
FY21 Unspent Funds	**$131,070**					**FY22 Unspent Funds**	**$4,259**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to change in staff and crediting warehouse staff hours for tribal and stakeholder river trips.
- Underspent funds for Travel & Training were due to travel restrictions associated with COVID-19.
- Overspent funds in Operating Expenses is due to the rescheduled Channel Mapping river trip from project B from FY21 that was completed in FY22.
- 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	**Principal Investigator(s) (PI)**	Lucas Bair, USGS, GCMRC
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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 (Petty, 2019).

Operational experiments include proposed experiments in the LTEMP EIS (U.S. Department of Interior, 2016b) and other identified operational scenarios at Glen Canyon Dam to improve hydropower and energy resources, while consistent with improvement and long-term sustainability of other downstream resources. Project N will prioritize monitoring and research of proposed experiments in the LTEMP EIS and consider impacts of other proposed experiments on hydropower and energy as part of the experimental design. Coordinated project implementation and development will occur between Reclamation, Western Area Power Administration (WAPA), and other collaborators to utilize and build on existing hydropower and energy models and data, specifically from Appendix K in the LTEMP EIS (U.S. Department of Interior, 2016b).

Science Questions Addressed & Results

In 2021, Lucas Bair collaborated with researchers from the University of California at Davis to develop a quadratic programming model to optimize the production of hydropower at Glen Canyon Dam (GCD). The hydropower optimization model closely follows Harpman (1999). 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 to manage downstream physical and biological recourses, including under different future power system scenarios. This model will be published as part of the research in Project J.1.

We assume that hydropower generated from the 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 Interior, 2016b).

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 (U.S Department of 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 Interior, 2016b for a full list of the operational constraints).

Here we provide an example of the hydrograph that the hydropower optimization model generates with and without a TMF. The baseline prices used to estimate the optimal TMF implementation are from PLEXOS (Bain and Aker, 2019) and Aurora (U.S. Department of Interior, 2016b) cost production model runs for 2024. Using production cost models to estimate prices allows for evaluation under a variety of future fuel costs and renewable energy capacity expansions scenarios. These results from the hydropower optimization models (Figure 1) are consistent with past analysis (U.S. Department of 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.

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 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 Interior, 2016b).

In FY 2023, GCMRC will continue to coordinate with internal and external partners, including Western Area Power Administration and the U.S. Department of Energy, to investigate how the management of GCD and the maintenance and improvement of downstream resources may provide opportunities to improve hydropower and energy resources. This coordination includes model development and application to different proposed TMF hydrographs (Giardina and others, in final edit with USGS Science Publishing Network) and the integration of hydropower costs associated with high-flow experiments and sediment resources (Mueller and Grams, 2021; Project J.1).

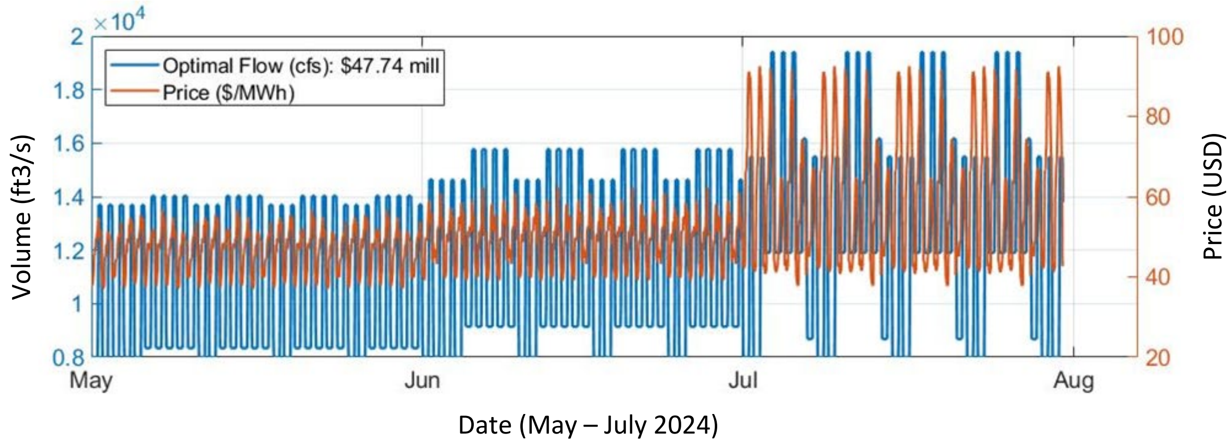

Figure 1. Optimal dispatch for hydropower production. Preliminary, do not cite.

References

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Bair, L.S. and Bain, D.M., 2019, Identifying the total economic value of hydropower at Glen Canyon Dam and implications for adaptive management, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 13, Phoenix, AZ. https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReprotingMeeting-IdentifyingTotalEconomicValueHydropowerGlenCanyonDam-Presentation-508-UCRO.pdf

Giardina, M.A., Korman, J., Yard, M., Wright, S., Kaplinski, M., and Bennett, G., *in final edits with the USGS Science Publishing Network*, A literature review and hypsometric analysis to support decisions on trout management flows on the Colorado River downstream from Glen Canyon Dam: U.S. Geological Survey Open-File Report.

Harpman, D.A., 1999, Assessing the short-run economic cost of environmental constraints on hydropower operations at Glen Canyon Dam: Land Economics, v. 75, no. 3, p. 390-401, https://doi.org/10.2307/3147185.

Mueller, E.R., and Grams, P.E., 2021, A morphodynamic model to evaluate long-term sandbar rebuilding using controlled floods in the Grand Canyon: Geophysical Research Letters, v. 48, no. 9, e2021GL093007, https://doi.org/10.1029/2021GL093007.

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

U.S. Department of Interior, 2016a, Record of decision for the Glen Canyon Dam long-term experimental and management plan final environmental impact statement (LTEMP ROD): Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region, http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf.

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Waldo, S., Deemer, B.R., Bair, L.S., and Beaulieu, J.J., 2021, Greenhouse gas emissions from an arid-zone reservoir and their environmental policy significance—Results from existing global models and an exploratory dataset: Environmental Science and Policy, v. 120, p. 53-62, https://doi.org/10.1016/j.envsci.2021.02.006.

Project N Budget

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$16,180	$1,500	$2,500	$0	$0	$2,487	**$22,667**
Actual Spent	$18,314	$0	$0	$0	$0	$2,257	**$20,571**
(Over)/Under Budget	**($2,134)**	**$1,500**	**$2,500**	**$0**	**$0**	**$230**	**$2,096**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$2,096**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Overspending Salaries is due to higher employee salary costs.
-Underspent Travel & Training is due to cancellations assocaited with COVID-19.
-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

Presentations:

Bair, L.S., and Bain, D.M., 2021, Identifying the total economic value of hydropower and implications for adaptive management of rivers—Operating restrictions of hydroelectric plants and their impacts on the operation of the Brazilian electric system—virtual presentation: XXIV Brazilian Symposium on Water Resources, November 2021.

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., 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 Joel Sankey, USGS, GCMRC Emily Palmquist, USGS, GCMRC Kimberly Dibble, NPS (formerly with USGS, GCMRC) Kirk Young, USFWS, AZ Fish and Wildlife Conservation Office Helen Fairley, USGS, GCMRC Lucas Bair, USGS, GCMRC Michael Runge, USGS, Eastern Ecological Science Center
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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 Long-Term Experimental and Management Plan EIS (U.S. Department of Interior, 2016a) and the only approved tool for rebuilding sandbar habitats that are eroded by dam operations and diminished sediment supply.

For many resources, spring-timed HFEs would be ideal: the pre-dam hydrograph had snowmelt-driven spring peaks, native fish, insect, and plants have life cycles that are adapted to spring high flows, the main recreational boating season that drives 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 High-Flow Experiments most often occur in 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 was to identify whether a Spring Disturbance Flow within the constraints of the LTEMP ROD (U.S. Department of 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

Damming changes the physical and chemical characteristics of a river and often eliminates flood disturbance, which allows invasive species that are adapted to constant flow environments to colonize impacted river reaches. Field experiments that test how the frequency and intensity of flood or low flow events affect invasive species have shown reductions in invasive species abundances following these disturbances. However, these studies are difficult to perform at ecological meaningful scales and often not replicated. Mathematical models offer a solution because they can predict the outcomes of various flows on invertebrate communities to inform management decisions. Collaborators at Oregon State University have developed a framework for a coupled, multi-species stage-structured model that can forecast how the timing, frequency, and magnitudes of flow events (i.e., extreme high and low flows such as occurred during the spring disturbance flow), water temperatures, and routine hydropower operations interact to impact native and invasive aquatic invertebrate populations in the Colorado River below Glen Canyon Dam.

Model outputs can be used to extract sensitivity networks that allow further understanding of the specific interactions between species and the relative strengths of these interactions within the aquatic invertebrate assemblage. The framework will be useful for identifying flow management scenarios that will, for example, optimize important prey items for desired fish, optimize native invertebrate species' populations, and generally characterize interspecific interactions between aquatic invertebrates in Grand Canyon. Of the species included in the model, three are invasive (*Potamopyrgus antipodarum*, New Zealand mud snail; *Gammarus lacustris*, amphipod; *Dreissena bugensis*, quagga mussel) while the other four are native taxa (*Hydropsyche osleria*, net-spinning caddisfly; Chironomidae, midges; Simuliidae, blackflies; Baetidae, Baetid mayflies). This multispecies mechanistic model will inform management discussions about invertebrate community response to novel flows caused by experimental flows, ongoing drought, and other flow regime shifts.

Water-Quality Monitoring at Lees Ferry

The Lees Ferry gage house is in stagnant water at flows less than 11,000 ft/s, and biological oxygen demand in the area is high owing to abundant submerged vegetation upstream. Resulting nighttime sags in dissolved oxygen at the gage are severe, such as nighttime readings in 2022 of < 0.5mg/L at the gage when, in reality, the main channel was 3-4mg/L dissolved oxygen. USGS has tried repeatedly to move sondes that are hardwired to the gage progressively farther into the channel to get accurate dissolved oxygen readings, but the local geomorphology prevents meters from being deployed in the main current. GMCRC maintains a sonde that is deployed from a buoy at Lees Ferry to ensure an accurate dissolved oxygen record, but this cannot be wirelessly connected to the gage to allow public access to the data in real time.

To support accurate water-quality monitoring during low flows, in FY 2022 GCMRC purchased a new buoy and water-quality monitor that will be deployed at Lees Ferry and wirelessly connected to the gage house to provide real-time and publicly accessible data on dissolved oxygen and other parameters of interest. This equipment was not in the original proposal for Project O.1, but it relates to the objectives and focus of Project O, i.e., predicting and monitoring ecosystem response to low flows.

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

For Project O.2, Bank Erosion, Bed Sedimentation, and Channel Change in Western Grand Canyon, we completed processing of the channel bathymetric and lidar data that were collected in 2021. These data consist of five repeat surveys of the riverbed and the banks for a 3.2 km reach beginning at RM 273. The surveys were completed in March, June, and September 2021 and include measurements made before, during, and immediately following the high flow pulse of the Spring Disturbance Flow. We presented preliminary analyses showing areas of erosion and deposition at the January 2021 Glen Canyon Dam Adaptive Management Program (GCAMP) Annual Reporting Meeting. In FY 2023, we will complete analyses of these data sets and prepare a final report for the project.

Element O.3 Aeolian Response to a Spring Pulse Flow

Along the Colorado River in Grand Canyon National Park, windblown river sand provides important wildlife habitat, sandy areas for camping, and a protective cover for archaeological sites but has decreased since construction of the upstream Glen Canyon Dam. One river management tool for increasing windblown sand is to release artificial "floods" from the dam to deposit sand above the level of typical river flows so it can be redistributed by wind. An alternative approach could be to lower river flows and expose sand that is usually underwater, allowing it to dry sufficiently to be moved by wind. During the 2021 spring disturbance flow we examined whether reducing flows to a low level (stage) for five days increases windblown sand. We learned that 48 hours after water stage dropped, a formerly wet sandbar had dried sufficiently so that wind speed, rather than dry sand abundance, had become the main factor limiting the amount of windblown sand. After 72 hours, the ability of wind to transport sand from the previously submerged sandbar was equivalent to an adjacent sand dune that was never inundated. These results show that low steady flows combined with wind offer an alternative to flooding for maintaining sandy landscapes in river valleys (Sankey and others, 2022).

Element O.11. Decision Analysis

Low Lake Powell 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 elevation 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 FLAHG charge, and the research proposed in 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.' The low Lake Powell elevation has created additional challenges related to spring disturbance flows including moving water supply from the Upper to Lower Colorado River Basins, 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, resources 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 will be used to support the objective, including collaborations with researchers at Utah State University who are modeling hydrology, operational alternatives, and future scenarios.

References

Sankey, J.B., Caster, J., Kasprak, A., and Fairley, H., 2022, The influence of drying on the aeolian transport of river-sourced sand: JGR Earth Surface, v. 127, no. 12, e2022JF006816, p. 1-24, https://doi.org/10.1029/2022JF006816.

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Project O Budget

Project O	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$230,993	$12,000	$5,000	$25,885	$40,667	$31,344	**$345,889**
Actual Spent	$50,443	$1,411	$25,047	$168,500	$0	$14,534	**$259,935**
(Over)/Under Budget	**$180,550**	**$10,589**	**($20,047)**	**($142,615)**	**$40,667**	**$16,810**	**$85,954**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$85,954**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Project O is entirely funded through FY21 unspent funds.
- Underspent Salaries were covered by USGS employees as well as through CESU cooperative agreements with Oregan State University and Utah State University.
-Overspent Operating Expenses is a contract with Marda Science for Riverbed Vegetation mapping awarded in FY22 instead of FY21.
-Overspent amount in Cooperative Agreement is due to change in mechanism for completing work through CESU cooperative agreements.

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

Presentations:

Bair, L.S. and Neher, C., 2022, Recreational anglers' preferences for flow attributes—Taking advantage of a designer flow to validate novel scenarios—virtual presentation: The International Institute of Fisheries Economics & Trade, Vigo, Spain, July 18-22, 2022.
Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B., Dibble, K., Tusso, R., and Bair, L., 2022, Spring disturbance flow update—virtual presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.
Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B., Dibble, K., Tusso, R., and Bair, L., 2022, Spring disturbance flow update—virtual presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022.
Kurthen, A.L, Lytle, D.A., and Kennedy, T.A., 2022, Developing a mechanistic modeling framework for aquatic invertebrate communities in dammed rivers: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Journal Articles:

Butterfield, B.J. and Palmquist, E.C., *in review*, Divergent physiological responses of hydric and mesic riparian plant species to a Colorado River experimental flow: Plant Ecology.
Sankey, J.B., Caster, J., Kasprak, A., and Fairley, H., 2022, The influence of drying on the aeolian transport of river-sourced sand: JGR Earth Surface, v. 127, no. 12, e2022JF006816, p. 1-24, https://doi.org/10.1029/2022JF006816.

Appendix 1: Lake Powell Water-Quality Monitoring

Program Manager (PM)	Bridget Deemer	**Principal Investigator(s)** (PI)	Bridget Deemer, USGS, GCMRC Nick Voichick, USGS, GCMRC Tom Sabol, USGS, GCMRC Caitlin Andrews, USGS, GCMRC Bryce Mihalevich, USGS, GCMRC
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Lake Powell received 6.1 million acre feet (maf, 64% of the 1991-2021 average) of unregulated inflow in water year (WY) 2022. This included approximately 500 thousand acre-feet (kaf) of water from Flaming Gorge Reservoir under the Drought Contingency Plan. In comparison, inflow observed in WY 2021 was 3.5 maf (36% of the 1991-2021 average), the second driest year on record after 2002. At the end of WY 2022, Lake Powell's surface elevation was 3529.33 feet (171 feet from full pool) with a storage of 5.80 maf, or 25% of live capacity. This is down from the end of WY 2021 when surface elevation was 3545.98 ft and storage was 7.27 maf. Releases for WY 2022 totaled 7 maf (as compared to 8.23 in WY 2021) consistent with operations under the 2007 Interim Guidelines. Operations for WY 2023 will fall under the Lower Elevation Balancing Tier, where Lake Powell and Lake Mead will balance contents with Glen Canyon Dam (GCD) release volumes no less than 7.0 maf and no more than 9.5 maf. The total projected annual release volume is currently 7.0 maf, with the October most probable (median) forecast projecting 8.1 maf of annual inflow to Lake Powell in WY 2023 (84% of average). Reclamation will evaluate hydrologic conditions in April 2023 to determine if balancing releases may be appropriate under the conditions established in the 2007 Interim Guidelines.

Glen Canyon Dam releases temperatures reached a record maximum of 21.1 °C on September 22, 2022 (Figure 2), which is markedly warmer than the peak of 16.8 °C on September 22, 2021, and unprecedented in the last 50 years (Figure 1). Prior to 2022, the peak instantaneous water temperature measured at Lees Ferry had not exceeded 17.2°C in over 50 years. This year the peak Lees Ferry water temperature measured was 21.4°C. These high temperatures are consistent with a recent trend wherein peak temperatures in GCD releases have exceeded 15 °C in 5 of the 8 previous years. Still, the Glen Canyon release temperatures in 2022 are unprecedented. Specifically, the 122 daily average water temperatures recorded at Lees Ferry between June 23 and October 22, 2022, were the warmest 122 water temperatures recorded in the preceding 50 years. These historically warm water temperatures, combined with relatively low soluble reactive phosphorus concentrations, are projected to cause a collapse in the rainbow trout fishery as soon as next year if low water levels continue (Korman and others, 2022). The warm waters also increase the likelihood of establishment of nonnative smallmouth bass and other warm-water nonnative fish below Glen Canyon Dam, which poses a serious threat to conservation of native fish (Bruckerhoff and others, 2022).

In the summer of 2022, layers of low dissolved oxygen water developed in all three major tributary arms of Lake Powell (Colorado, the San Juan, and Escalante Rivers). Similar low dissolved oxygen events have developed in the past (namely in 2005, 2014, 2019, and 2021). This low dissolved oxygen was advected toward the forebay, with a minimum dissolved oxygen concentration of about 0.4 mg/L at 20 m depth in October 2022. This advection resulted in record low concentrations of DO in the GCD tailwaters (minimum DO of 2.5 mg/L in September of 2022 as compared with 4.0 mg/L in Octobers of 2019 and 2021, 4.4 mg/L in October 2014, and 3.5 mg/L in 2005; Figure 1). The 2005 low dissolved oxygen event coincided with much lower recruitment and growth in the Glen Canyon rainbow trout fishery (Korman and others, 2012), so the low dissolved oxygen observed in Glen Canyon is of concern. The National Park Service continues to track and monitor the quagga mussel population throughout Lake Powell, mainly by estimating veliger densities in zooplankton tows.

Summary of FY 2022 Accomplishments

In fiscal year (FY) 2022, the GCMRC collected physical, biological, and chemical data and samples from Lake Powell, GCD, and Lees Ferry. This included four reservoir-wide surveys in collaboration with Reclamation as well as nine complete forebay surveys (Table 1). GCMRC also checked, reprogrammed, and replaced temperature and conductivity loggers on a thermistor string that is deployed off the buoy line near GCD in March of 2022 (and again in October of 2022).

GCMRC continued development of a Microsoft SQL Server database and a linked custom application that allows for streamlined data import, export, and online data visualization. In August of 2021, USGS submitted a U.S. Geological Survey ScienceBase data release (Andrews and Deemer, 2022) and an associated data paper (Deemer and others, 2023) describing the long-term water-quality monitoring data set (Deemer and others, 2023). The ScienceBase data set is a dynamic data release containing 8 flat files (Figure 2) that is 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). USGS plans to update this repository annually. The database is also linked to Tableau and USGS scientists are currently developing data visualizations to share with their colleagues at Reclamation (Hensleigh and others, 2022), with the eventual intention to make some visualizations public with the data release.

In FY 2022, GCMRC also continued to maintain the sonde directly below GCD 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, which is currently being shared with colleagues at Reclamation as well as several interested stakeholders (see Project K for more information). Efforts are underway to make this visualization public (Gushue and Thomas, 2021).

Postdoctoral researcher, Bryce Mihalevich, began working for GCMRC in June of 2022 with the goal of improving the Lake Powell CE-QUAL-W2 model. Mihalevich and Deemer attended a CE-QUAL-W2 workshop held at Portland State University from June 20-24, 2022.

As of October 2022, a new grid structure has been developed that reflects a new bathymetric data set for Lake Powell (Jones and Root, 2021) and that performs under low reservoir water levels. Mihalevich is currently continuing to develop the CE-QUAL-W2 model to improve meteorological inputs and to incorporate long-term water-quality data. Deemer also conducted water and sediment incubations with dry deltaic sediments in FY 2022 to examine controls on oxygen consumption and phosphorus release with funding from outside the Lake Powell program. These findings will be used to inform the dissolved oxygen module of the CE-QUAL-W2 model.

During FY 2022, PI Deemer worked with Technical Information Specialist, Meredith Hartwell, to develop a website for the Lake Powell Water-Quality Monitoring Program (https://www.usgs.gov/centers/southwest-biological-science-center/science/lake-powell-research). The page provides some basic facts about Lake Powell, describes the ongoing water-quality monitoring program, and describes some active areas of current research. We plan to use this page as a launching point for publicly available data visualizations once the data release is finalized.

Funding Note

The Lake Powell monitoring program was designed to determine status and trends of the water-quality of Lake Powell and GCD releases, determine the effect of climate patterns, hydrology, and dam operations on reservoir hydrodynamics and the water-quality of GCD 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 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.

An interagency agreement was signed in FY 2018, which has supported GCMRC involvement in the Lake Powell Water-Quality Monitoring program over the past five years. A scope of work and budget is currently drafted toward the development of a new interagency agreement. 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 was appended to the original Interagency Agreement and additional funding for FY 2023 is planned.

Table 1. Beginning dates and sampling activity for the Lake Powell water-quality monitoring for FY 2022.

Date	Sampling Activity
10/20/21	Forebay, draft tubes, Lees Ferry
11/17/21	Forebay, draft tubes, Lees Ferry
12/13/21	Quarterly Survey
1/12/22	Forebay, draft tubes, Lees Ferry
2/9/22	Forebay, draft tubes, and Lees Ferry
3/7/22	Quarterly Survey
4/19/22	Forebay, draft tubes, and Lees Ferry
5/16/22	Forebay, draft tubes, and Lees Ferry
06/13/22	Quarterly survey
7/26/22	Forebay, draft tubes, and Lees Ferry
8/26/22	Forebay, draft tubes, and Lees Ferry
9/19/22	Quarterly survey

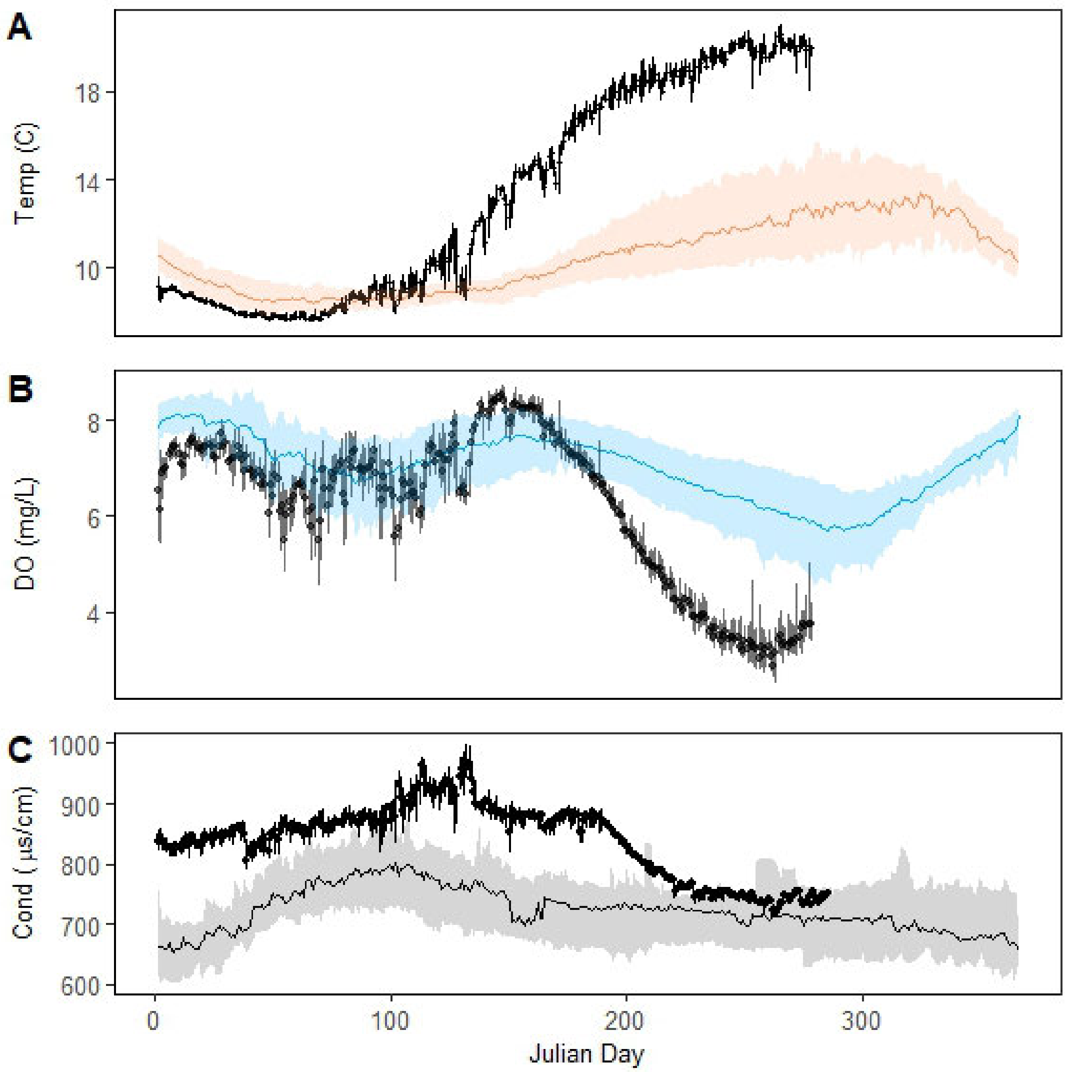

Figure 1. Water-quality record from Glen Canyon Dam near Page, AZ (gage #09379901; U.S. Geological Survey, 2022), for temperature (A) and dissolved oxygen (B) as well as conductivity data from the Colorado River at Lees Ferry (gage # 09380000; panel C). Black points show daily median values from 2022 and black bars show minimum and maximum values for each day in 2022 from the continuous data record (logging at 15-minute increments). Lines and bands show the 13-year median value for each parameter and the red, blue, and gray color bands represent the daily 10th and 90th quantiles of 13-year temperature, dissolved oxygen, and conductivity, respectively.

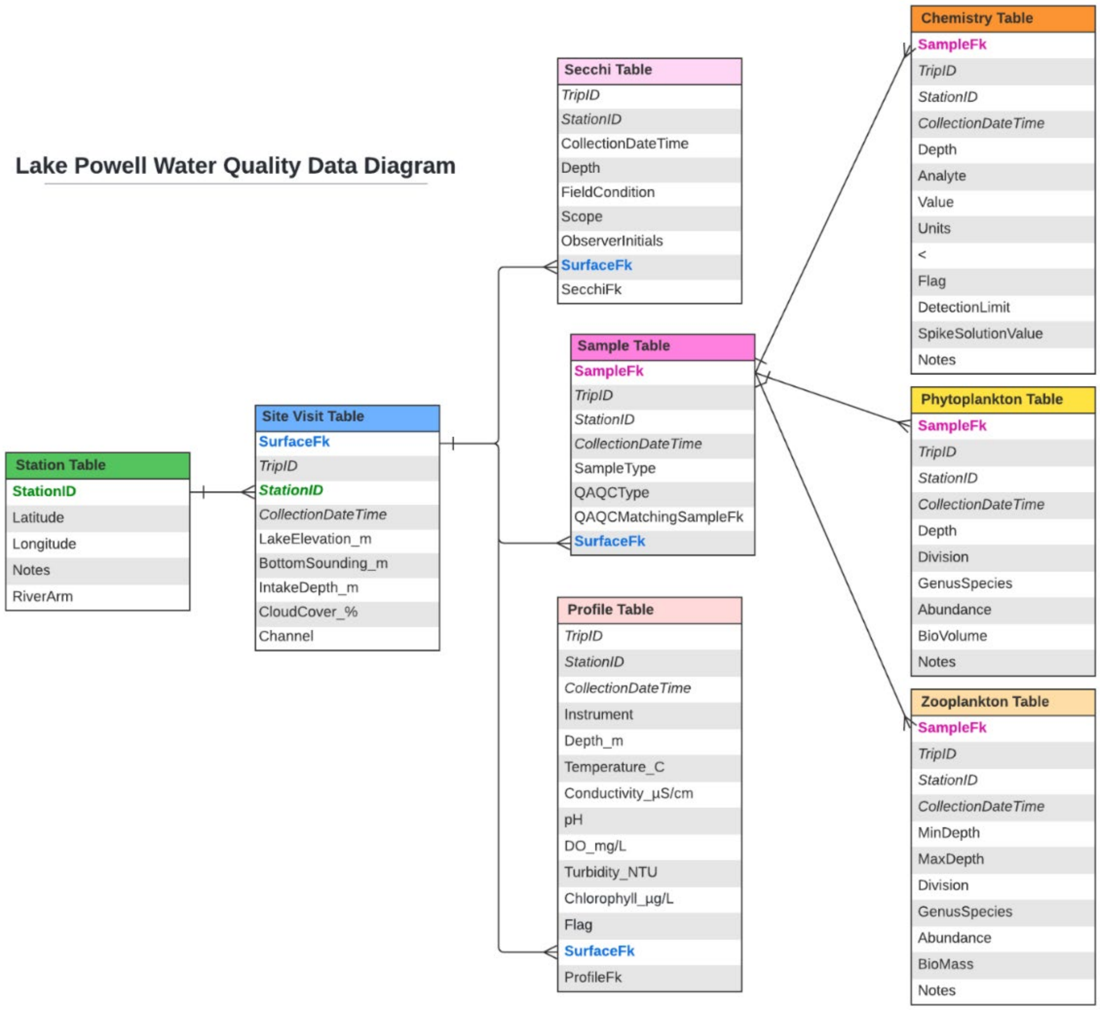

Figure 2. Schema diagram showing the eight flat files that comprise the Lake Powell data set being released (Andrews and Deemer 2022; Deemer and others, 2023).

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Andrews, C.M., and Deemer, B.R., 2022, Limnology data from Lake Powell, desert southwest USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZIKVYW.

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Korman, J., Martell, S.J.D., Walters, C.J., Makinster, A.S., Coggins, L.G., Yard, M.D., and Person, W.R., 2012, Estimating recruitment dynamics and movement of rainbow trout (*Oncorhynchus mykiss*) in the Colorado River in Grand Canyon using an integrated assessment model: Canadian Journal of Fisheries and Aquatic Sciences, v. 69, no. 11, p. 1827-1849, http://doi.org/10.1139/f2012-097.

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Appendix 1 Budget

Lake Powell (NOT GCDAMP funded)							
	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 20.163%	Total
Budgeted Amount	$145,065	$8,814	$11,968	$0	$0	$33,440	**$199,287**
Actual Spent	$188,290	$5,699	$24,507	$0	$0	$44,055	**$262,551**
(Over)/Under Budget	**($43,225)**	**$3,115**	**($12,539)**	**$0**	**$0**	**($10,615)**	**($63,264)**
Unspent Funds	**$63,264**					**2022 Unspent Funds**	**$0**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- This project is funded entirely by Reclamation with non-GCDAMP funding.
- This agreeemnt period of performance ended 12/31/2022 and shows all funding expended through the calendar year.
- Overspent Salaries is due to this agreement being on the calendar year rather than the fiscal year and actual salary overspending is between 9/30/22 and 12/31/2022 when the agreement ended.
- Underspent Travel & Training were due to travel restrictions associated with COVID-19.
-Overspent Operating Expenses is for a Sonde and equipment purchase that was made after the fiscal year.
-All funds have been expended at the end of the calendar year and a new 5 year agreeement start date is 1/1/2023-12/31/2027

Appendix 1 Deliverables: Lake Powell Water-Quality Monitoring

Presentations:

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

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, online, https://doi.org/10.1002/lol2.10310.

USGS Data Releases:

Andrews, C.M., and Deemer, B.R., 2022, Limnology data from Lake Powell, desert southwest USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZIKVYW.

Web Content and Applications:

Deemer, B.R., 2022, Lake Powell research—webpage: U.S. Geological Survey Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, https://www.usgs.gov/centers/southwest-biological-science-center/science/lake-powell-research.

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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:

Because the COVID-19 pandemic is only now ending, no presentations were made at professional scientific meetings during FY 2022. One presentation was made to the GCDAMP at the January 2022 Annual Reporting Meeting.

Journal Articles:

Deemer, B.R., Yackulic, C.B., Hall, R.O., Dodrill, M.J., Kennedy, T.A., Muehlbauer, J., Topping, D.J., Voichick, N., and Yard, M., 2022, Daily flow fluctuations associated with hydropower generation reduce gross primary productivity up to 400 kilometers downstream in a regulated river: Proceedings of the National Academy of Sciences NEXUS, v. 1, p. 1–12, https://doi.org/10.1093/pnasnexus/pgac094.

LeCoz, J., Perret, E., Camenen, B., Topping, D.J., Buscombe, D.D., Leary, K.C.P, Dramais, G., and Grams, P.E., *in press*, Mapping 2-D bedload rates throughout a sand-bed river reach from high-resolution acoustical surveys of migrating bedforms: Water Resources Research, https://doi.org/10.1029/2022WR032434.

USGS Reports:

Griffiths, R.E., Topping, D.J., and Unema, J.A., *in review*, 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.

Sabol, T.A., Topping, D.J., Griffiths, R.E., and Dramais, G., 2022, Field investigation of sub-isokinetic sampling by the US D-96-type suspended-sediment sampler and its effect on suspended-sediment measurements: U.S. Geological Survey Open-File Report 2022-1077, 14 p., https://doi.org/10.3133/ofr20221077.

Topping, D.J., Hazel, J.E., Jr., Kaplinski, M., and Grams, P.E., *in press* at the USGS Science Publishing Network, 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.

Web Applications:

- https://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 has been maintained to provide 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.

- https://waterdata.usgs.gov/nwis - Stage, discharge, and water-quality data collected at 9 gaging stations by the USGS Utah and Arizona Water Science Centers are posted to this website every hour.

Project B Deliverables: Sandbar and Sediment Storage Monitoring and Research

Presentations:

Grams, P.E., 2022, The effects of high-flow experiments and dam releases on sandbar erosion and deposition in Marble and Grand canyons: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.

Grams, P.E., 2022, Sediment dynamics in western Grand Canyon during 2021 Spring disturbance flow: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.

Grams, P.E., 2022, Summary of sediment and sandbar projects—GCMRC Projects A and B, LTEMP Goal 7: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022.

Grams, P.E. and Mueller, E.R., 2022, Predicted effects of alternative summer 2022 release scenarios on sediment and sandbars: Glen Canyon Dam Adaptive Management Program Webinar on Glen Canyon Dam Summer 2022 Release Pattern, March 2022.

Grams, P.E., 2022, Multi-decadal sandbar response to flow management downstream from a large dam—The Colorado River in Marble and Grand canyons, Arizona: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, August 2022.

Mueller, E.R., and Grams P.E., 2021, A morphodynamic model to evaluate long-term sandbar rebuilding using controlled floods: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, October 2021.

USGS Reports:

Hazel, J.E., Kaplinski, M.A., Hamill, D., Buscombe, D., Mueller, E.R., Ross, R.P., Kohl, K., and Grams, P.E., 2022, Multi-decadal sandbar response to flow management downstream from a large dam—The Glen Canyon Dam on the Colorado River in Marble and Grand Canyons, Arizona: U.S. Geological Survey Professional Paper 1873, prepared in cooperation with Northern Arizona University, 104 p., https://doi.org/10.3133/pp1873.

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., Gushue, T.M., Buscombe, D., and Kohl, K., 2022, Channel mapping of the Colorado River from Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona: U.S. Geological Survey Open-File Report 2022-1057, 20 p., https://doi.org/10.3133/ofr20221057.

USGS Data Releases:

Kaplinski, M., Hazel, J.E. Jr, Grams, P.E., Gushue, T., Buscombe, D.D., and Kohl, K., 2022, Channel mapping Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona - Data: U.S. Geological Survey data release, https://doi.org/10.5066/P98GFP93.

Web Applications:

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

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

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

Project C Deliverables: Riparian Vegetation Monitoring and Research

Presentations:

Butterfield, B.J. and Palmquist, E.C., 2022, Riparian vegetation monitoring and modeling—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 12, 2022.

Butterfield, B.J., Palmquist, E.C., and Yackulic, C.B., 2022, The hydroclimatic niche—A tool for predicting and managing riparian plant community responses to streamflow seasonality—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, September 12-15, 2022, Flagstaff, AZ.

Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B.J., Dibble, K., Bair, L., and Tusso, R., 2022, Disturbance Flow Panel Session—presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 12, 2022.

Palmquist, E., Ogle, K., Butterfield, B.J., Whitham, T., Shafroth, P., and Allan, G., Provenance of a riparian shrub changes traits but not flood response under a common climatic setting: River's Edge West 20th Anniversary Riparian Restoration Conference, February 23-25, 2022, Grand Junction, CO.

Palmquist, E.C., 2022, Goal 11: Riparian Vegetation Draft Metrics—presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, April 13, 2022.

Palmquist, E.C., Ogle, K., and Butterfield, B.J., Riparian plant presence and abundance are differentially controlled by hydrology and temperature along a regulated, dryland river—presentation: 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, September 12-15, 2022, Flagstaff, AZ.

Pilkington, L., Stevens, L., Burke, K., Butterfield, B.J., Palmquist, E., and Sankey, J., 2022, Riparian vegetation science & management—webinar presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 9-10, 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/amwg.html.

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Samuels-Crow, K., Ogle, K., and Palmquist, E.C., 2022, What drought means for southwestern landscapes: Boatman's Quarterly Review, v. 35, no. 1, p. 16-19. (Article not available online)

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Palmquist, E.C., Butterfield, B.J., and Ralston, B.E., 2022, Riparian vegetation data downstream of Glen Canyon Dam in Glen Canyon National Recreation Area and Grand Canyon National Park, AZ, from 2014 to 2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9KEHY2S.

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

Presentations:

Fairley, H.C., Scott, M., and Fairley, A.H., 2022, Assessing 50 years of change in riparian condition along the Colorado River in Grand Canyon, Arizona—presentation: 16th Biennial Conference on Science and Management, Flagstaff, AZ, September 15, 2022.

Sankey, J.B., East, A., Fairley, H.C., Dierker, J., Brennan, E., Bransky, N., 2022, Risk of erosion of archaeological sites along the Colorado River in Grand Canyon owing to long term operations of Glen Canyon Dam—presentation: 16th Biennial Conference on Science and Management, Flagstaff, AZ, September 15, 2022.

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Caster, J., Sankey, J.B., Fairley, H., and Kasprak, A., 2022, Terrestrial lidar monitoring of the effects of Glen Canyon Dam operations on the geomorphic condition of archaeological sites in Grand Canyon National Park, 2010–2020: U.S. Geological Survey Open-File Report 2022–1097, 100 p., https://doi.org/10.3133/ofr20221097.

Pilkington, L., Sankey, J.B., Boughter, D., Preston, T., Prophet, C.C., 2022, Parks look for ways to alleviate Glen Canyon Dam's dramatic downstream impacts: Park Science Magazine, National Park Service, Glen Canyon National Recreation Area, Grand Canyon National Park, v. 36, no. 1, Summer 2022, https://www.nps.gov/articles/000/parks-look-for-ways-to-alleviate-glen-canyon-dams-downstream-impacts.htm.

Sankey, J.B., Caster, J., Kasprak, A. and Fairley, H., 2022, The influence of drying on the aeolian transport of river-sourced sand: Journal of Geophysical Research: Earth Surface, v. 127, no. 12, e2022JF006816, p. 1-24, https://doi.org/10.1029/2022JF006816.

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

Presentations:

Bruckerhoff, L., Wheeler, K., Dibble, K., Mihalevich, B., Neilson, B., Wang, J., Yackulic, C., and Schmidt, J., 2022, Water storage decisions and consumptive use constrain ecosystem management under severe sustained drought—virtual presentation: Desert Fishes Council 2022 Annual Meeting, St. George, Utah.

Deemer, B.R., 2022, Beyond eco-flow—Understanding biogeochemical links between limnology and management in human-made reservoirs—presentation: Joint Aquatic Science Meeting (JASM 2002), Grand Rapids, MI.

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 and Management on the Colorado Plateau and Southwest Region, Flagstaff, AZ.

Deemer, B., Yackulic, C., Hall, R., Dodrill, M., Kennedy, T., Muehlbauer, J., Topping, D., Voichick, N., and Yard, M., 2022, Turning the red river green: An experimental flow increases primary production in the Colorado River—presentation for Friday's Findings webinar, U.S. Geological Survey Ecosystems Mission Area, Reston, Va., January 14, 2022, U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Dibble, K.L., 2022, 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, Flagstaff, AZ.

Dibble, K.L., Bruckerhoff, L.A., Yackulic, C.B., Schmidt, J.C., Bestegen, 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—Oral presentation and virtual panel for the Department of Interior's Turbine Talk Webinar Series focused on 'USGS Science on Climate Impacts on Hydropower'.

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Journal Articles:

Deemer, B.R., Reibold, R., Fatta, A., Corman, J.R., Yackulic, C.B., and Reed, S.C., *submitted*, pH of dam releases affects downstream phosphorus cycling in an arid regulated river: Ecological Applications.

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.

Hansen, L.E., Yackulic, C.B., Dickson, B.G., Deemer, B.R., and Best, R.J., *submitted*, 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.

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, online, 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.

Yackulic, C. B., M. D. Yard, J. Korman, M. J. Dodrill, and B. R. Deemer. 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., 2022, Background and design of the Bug Flows hydrograph—virtual presentation: Science Advisor review of the Bug Flow experiment, Day 1, October 2022.

Kennedy, T., 2022, Bug Flows and the rainbow trout fishery—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 1, October 2022.

Kennedy, T., 2022, Discussion of the Bug Flow synthesis and review and opportunities for Spring and Summer Flow Experiments—virtual presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, January 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T., 2022, Potential next steps in flow experimentation—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 2, November 2022.

Kennedy, T., and Muehlbauer, J., 2022, Project F—Aquatic ecology and food base monitoring—virtual presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 11-12, 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T. and Muehlbauer, J., 2022, Project F—Aquatic ecology and food base monitoring—virtual presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Kennedy, T.A., Muehlbauer, J.D., Deemer, B.R., Yackulic, C.B., Ford, M.A., Szydlo, C., Metcalfe, A.N., and Lytle, D.A., 2022, Experimental Bug Flows increase algae production and insect diversity in the Colorado River, Grand Canyon—presentation: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Kennedy, T.A., Muehlbauer, J.D., Deemer, B.R., Yackulic, C.B., Ford, M.A., Szydlo, C., and Metcalfe, A.N., 2022, Experimental 'Bug Flows' increased algae production and insect diversity in the Colorado River, Grand Canyon: 16th Biennial Conference of Science and Management for the Colorado Plateau, Flagstaff, AZ, September 2022.

Freedman, J.W., Burke, M.K., Kennedy, T.A., and Lytle, D.A., 2022, Environmental DNA metabarcoding reveals aquatic invertebrate community diversity in the Grand Canyon—presentation: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Metcalfe, A.N., Fritzinger, C.A., Kennedy, T.A., Dodrill, M.J., Muehlbauer, J.D., Holton, B., Durning, L.E., Sankey, J.B., and Weller, T., 2022, Bats, bugs, and boaters—Insectivorous bat foraging along the Colorado River in Grand Canyon is determined by the availability of aquatic flies: 16th Biennial Conference of Science and Management for the Colorado Plateau, Flagstaff, AZ, September 2022.

Metcalfe, A., Kennedy, T., Muehlbauer, J., Dodrill, M., Durning, L., Sankey, J., and Fritzinger C., 2022, The role of insect abundance and riparian vegetation in driving bat foraging activity in Grand Canyon—Insights from a community science project—virtual presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 11-12, 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

Metcalfe, A.N., Kennedy, T., Muehlbauer, J.D., Dodrill, M.J., Weller, T., Durning, L., Sankey, J.B., and C.A. Fritzinger, 2022, Insectivorous bat foraging along the Colorado River in Grand Canyon is determined by aquatic prey availability and tall vegetation density—presentation: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Muehlbauer, J., 2022, Bug Flows—Invertebrate response—virtual presentation: Science Advisor review of the Bug Flow Experiment, Day 1, October 2022.

Traynham, L. and Kennedy, K., 2022, "Potential LTEMP experiments Spring/Summer 2022—virtual presentation: Glen Canyon Dam Adaptive Management Program Technical Work Group Meeting, April 2022, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center.

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.

Kennedy, T.A., Metcalfe, A.N., Deemer, B.R., Ford, M.A., Szydlo, C.M., Yackulic, C.B., and Muehlbauer, J.D., 2022, Little bugs, big data, and Colorado River adaptive management—Preliminary findings from the ongoing bug flow experiment at Glen Canyon Dam: Boatman's Quarterly Review, v. 35, no. 3, p. 26-31. (Not available online)

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, online, https://doi.org/10.1139/cjfas-2022-0142.

Metcalfe, A., Kennedy, T., Fritzinger, C., Dodrill, M.J., Szydlo, C.M., Muehlbauer, J.D., Yackulic, C.B., Holton, B.P., Durning, L.E., Sankey, J.B., and Weller, T.J., *submitted*, Insectivorous bat foraging tracks the availability of aquatic flies (Diptera): Journal of Wildlife Management.

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

Presentations:

Bair, L.S., 2022, Adaptive management and cultural ecosystem services—virtual presentation: ACES, A Community on Ecosystem Services Conference, December 2022.

Bair, L.S., 2022, Consideration of plural values in integrated assessments—presentation: AGU Chapman Conference, on 'Solving Water Availability Challenges through an Interdisciplinary Framework', September 12-16, 2022.

Dzul, M.C., and Yackulic, C.B., 2022, Effects of flow, sediment, and nonnative fishes on age-0 population dynamics of humpback chub in the lower Little Colorado River—presentation: 16th Biennial Conference of Science and Management for the Colorado Plateau and Southwest Region, September 12-15, 2022, Flagstaff, AZ.

Journal Articles:

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

Dzul, M.C., Yackulic, C.B., Giardina, M., Yard, M., Van Haverbeke, D.R., *in prep,* Vital rates of a burgeoning population of humpback chub in western Grand Canyon.

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

USFWS Reports:

Van Haverbeke, D.R., Young, K.L., Pillow, M.J., and Rinker, P.N., 2022, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2021: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey Grand Canyon Monitoring and Research Center, 49 p.

Van Haverbeke, D.R., K.L. Young, M.J. Pillow, and Rinker, P.N., 2022, Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2021: Flagstaff, Ariz., U.S. Fish and Wildlife Service, USFWS Document no. USFWS-AZFWCO-22-04, 41 p.

Project H Deliverables: Salmonid Research and Monitoring

Journal Articles:

Crossman, J.A., Webb, M.A.H., Korman, J., and Yard, M.D., 2022, Population reproductive structure of rainbow trout determined by histology and advancing methods to assign sex and assess spawning capability: Transactions of the American Fisheries Society, v. 151, no. 4, p. 422-440, https://doi.org/10.1002/tafs.10356.

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, online, 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, online, 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 Reports:

Giardina, M.A., Korman, J., Yard, M., Wright, S., Kaplinski, M., and Bennett, G., *in final edits with the USGS Science Publishing Network*, A literature review and hypsometric analysis to support decisions on trout management flows on the Colorado River downstream from Glen Canyon Dam: U.S. Geological Survey Open-File Report.

USGS Data Releases:

Yackulic, C.B., Yard, M., Korman, J., Rogowski, D., Healy, B.D., Schelly, R.C., Omana-Smith, E., and Nelson, C., 2022, Brown trout movement data in Glen and Grand canyons, Arizona, USA: U.S. Geological Survey data release, https://doi.org/10.5066/P96NII4B.

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

Presentations:

Frye, E., and Ward D., 2022, Common carp, uncommon predator—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Frye, E., and Ward D., 2022, Green sunfish, aquatic gremlins of the southwest—poster presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Rogowski, R., 2022, Back to the future, warm-water fish in the Grand Canyon—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Ward D., and Frye, E., 2022, Oxygen manipulation for fisheries management—presentation: Desert Fishes Council 2022 Annual Meeting, November 16-18, 2022, Saint George, Utah.

Project J Deliverables: Socioeconomic Research in the Colorado River Ecosystem

Presentations:

Bair, L.S., and Bain, D.M., 2021, Identifying the total economic value of hydropower and implications for adaptive management of rivers—Operating restrictions of hydroelectric plants and their impacts on the operation of the Brazilian electric system—virtual presentation: XXIV Brazilian Symposium on Water Resources, November 2022.

Bair, L.S., 2021, Adaptive management and cultural ecosystem services—virtual presentation: ACES: A Community on Ecosystem Services conference, December 2022.

Bair, L.S. and Neher, C., 2022, Recreational anglers' preferences for flow attributes—Taking advantage of a designer flow to validate novel scenarios—virtual presentation: The International Institute of Fisheries Economics and Trade, July 18-22, Vigo, Spain.

Bair, L.S., 2022, Consideration of plural values in integrated assessments—presentation: AGU Chapman Conference on Solving Water Availability Challenges through an Interdisciplinary Framework, September 12-16, Golden, Colorado.

Journal Articles:

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

Hoelting, K., Morse, J.M., Gould, R., Martinez, D.E., Hauptfeld, R.S., Cravens, A.E., Breslow, S., Bair, L.S., Schuster, R.M., and Gavin, M.C., 2022, Opportunities for improved consideration of cultural benefits in environmental decision-making: SocArXiv, p. 1-42, https://doi.org/10.31235/osf.io/dpbe3.

Jungers, B., Abbott, J.K., Bair, L.S., *in prep*: Program evaluation of the Lees Ferry brown trout incentivized harvest program.

Project K Deliverables: Geospatial Science and Technology

Note: listed here are products that include Project K staff as authors; however, the work plan and budget for some products reside in other science projects.

Presentations:

Gushue, T.M., Andrews, C.M., and Thomas, J.E., 2022, Modernizing sensor data workflows to leverage Internet of Things (IoT) and cloud-based technologies—presentation: USGS Community for Data Integration monthly meeting, May 2022.

Gushue, T.M., Thomas, J.E., 2022, Modernizing sensor data workflows to leverage Internet of Things (IoT) and cloud-based technologies—presentation: USGS Cloud Hosting Solutions customer user group meeting, August 2022.

Gushue, T.M., Thomas, J.E., and Andrews, C.M., 2022, Modernizing data telemetry efforts for important riparian resources in the Grand Canyon—abstract for 16th Biennial Conference for Science and Management on the Colorado Plateau and Southwest Region, September 12-15, 2022: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz.

Thomas, J.E., Gushue, T.M., Andrews, C.M., and Unema, J., 2022, Using NWIS data from multiple gauging stations to capture event based video—presentation: USGS Community for Data Integration 2023 Request for Proposals Lightning Presentations.

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, online, https://doi.org/10.1002/lol2.10310.

USGS Reports:

Kaplinski, M., Hazel, J.E., Jr., Grams, P.E., Gushue, T.M., Buscombe, D., and Kohl, K., 2022, Channel mapping of the Colorado River from Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona: U.S. Geological Survey Open-File Report 2022-1057, 20 p., https://doi.org/10.3133/ofr20221057.

USGS Data Releases:

Andrews, C.M., and Deemer, B.R., 2022, Limnology data from Lake Powell, desert southwest USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9ZIKVYW.

Kaplinski, M., Hazel, J.E. Jr, Grams, P.E., Gushue, T.M., Buscombe, D.D., and Kohl, K., 2022, Channel mapping Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona - Data: U.S. Geological Survey data release, https://doi.org/10.5066/P98GFP93.

Manuals:

Thomas, J.E., 2022, Little Colorado River humpback chub Pit Tag master controller IoT system—User and maintenance manual: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/little-colorado-river-mux-antenna/-

/blob/main/Little_Colorado_River_Pit_Tag_Master_Controller_Manual_V1.pdf.

Thomas, J.E., 2022, Satellite remote relay design—User and maintenance manual, Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/iot-utilities/-/blob/main/Satellite%20Relay%20System/Satellite_Remote_Reboot_Manual_V1.pdf.

Thomas, J.E., 2022, Taylor Woods IoT Datalogger—User and maintenance manual: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, SBSC-GCMRC-IoT Gitlab repository, https://code.usgs.gov/sbsc/sbsc-gcmrc-iot/taylor-woods-iot-data-loggers/-/blob/main/Taylor_Woods_IoT_Datalogger_Manual_V2.pdf.

Websites & Web Applications:

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

Web Content on ESRI ArcGIS Online:

- 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
- 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

Online Data Visualizations:

Gushue, T.M, and Thomas, J.E., 2021, Daily Water-Quality Data at Glen Canyon Dam—online data visualization: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, https://tableau.usgs.gov/t/InternalGuestAccess/views/WaterQualityatGlenCanyonDam/DailyWaterQualityDataatGlenCanyonDam?%3Aembed=y&%3AisGuestRedirectFromVizportal=y#1.

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

Project N Deliverables: Hydropower Monitoring and Research

Presentations:

Bair, L.S., and Bain, D.M., 2021, Identifying the total economic value of hydropower and implications for adaptive management of rivers—Operating restrictions of hydroelectric plants and their impacts on the operation of the Brazilian electric system—virtual presentation: XXIV Brazilian Symposium on Water Resources, November 2021.

Journal Articles:

Donovan, P., Reimer, M.N., Springborn, M.R., Yackulic, C.B., Bain, D.M., 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:

Bair, L.S. and Neher, C., 2022, Recreational anglers' preferences for flow attributes—Taking advantage of a designer flow to validate novel scenarios—virtual presentation: The International Institute of Fisheries Economics & Trade, Vigo, Spain, July 18-22, 2022.

Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B., Dibble, K., Tusso, R., and Bair, L., 2022, Spring disturbance flow update—virtual presentation: Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting, January 2022.

Kennedy, T., Deemer, B., Lytle, D., Grams, P., Sankey, J., Butterfield, B., Dibble, K., Tusso, R., and Bair, L., 2022, Spring disturbance flow update—virtual presentation: Glen Canyon Dam Adaptive Management Program Adaptive Management Work Group Meeting, February 2022.

Kurthen, A.L, Lytle, D.A., and Kennedy, T.A., 2022, Developing a mechanistic modeling framework for aquatic invertebrate communities in dammed rivers: Joint Aquatic Sciences Meeting (JASM 2022), Grand Rapids, MI, May 2022.

Journal Articles:

Butterfield, B.J. and Palmquist, E.C., *in review*, Divergent physiological responses of hydric and mesic riparian plant species to a Colorado River experimental flow: Plant Ecology.

Sankey, J.B., Caster, J., Kasprak, A., and Fairley, H., 2022, The influence of drying on the aeolian transport of river-sourced sand: JGR Earth Surface, v. 127, no. 12, e2022JF006816, p. 1-24, https://doi.org/10.1029/2022JF006816.

Appendix 3: Budgets, All Projects

Project A Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$485,907	$10,000	$58,500	$0	$392,587	$68,336	**$1,015,330**
Actual Spent	$497,227	$2,431	$83,030	$0	$459,407	$71,822	**$1,113,917**
(Over)/Under Budget	**($11,320)**	**$7,569**	**($24,530)**	**$0**	**($66,820)**	**($3,486)**	**($98,587)**
FY21 Unspent Funds	**$135,000**					**FY22 Unspent Funds**	**$36,413**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent funds; etc.)*

FY22 Comments:
-Overspent Salaries during FY22 is due to shortfall in the budget for essential project staff.
-Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
-Overspent Operating Expenses was for instrument repairs and replacements initiated in Q4 FY22 that will be 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 B Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$382,144	$5,000	$32,000	$353,293	$0	$62,262	**$834,699**
Actual Spent	$436,289	$7,555	$48,891	$8,000	$0	$60,974	**$561,709**
(Over)/Under Budget	**($54,145)**	**($2,555)**	**($16,891)**	**$345,293**	**$0**	**$1,288**	**$272,990**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$272,990**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent; etc.)*

FY22 Comments:
-Overspent Salaries is due to bringing staff from other USGS centers and overtime associated with the Channel Mapping river trip that was rescheduled from FY21.
-Overspent Travel & Training is due to field work and the Channel Mapping river trip that was moved from FY21 to FY22 due to Covid-19.
-Overspent Operating Expenses is due to necessary Inertial Navigation System equipment rental for the Channel Mapping river trip.
-Underspent funds in Cooperative Agreements is due to personnel working on this project left Northern Arizona University and the agreement will not be continued. The work will be accomplished by increasing staff at GCMRC.

Project C Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$134,307	$3,940	$1,565	$107,337	$0	$20,453	**$267,602**
Actual Spent	$133,693	$2,129	$1,102	$109,097	$0	$20,150	**$266,170**
(Over)/Under Budget	**$614**	**$1,811**	**$464**	**($1,760)**	**$0**	**$303**	**$1,432**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$1,432**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated unspent; etc.)*

FY22 Comments:
-Underspent Salaries is due to technician turnover on this project.
-Underspent Travel & Training were to compensate for increased botanist costs. A local conference was attended instead of a national conference.
-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 12.326%	Total
Budgeted Amount	$214,084	$10,600	$2,806	$0	$0	$28,040	**$255,530**
Actual Spent	$208,980	$4,351	$14,417	$0	$0	$28,072	**$255,820**
(Over)/Under Budget	**$5,104**	**$6,249**	**($11,611)**	**$0**	**$0**	**($32)**	**($290)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($290)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to staff turnover at the end of the FY.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent amount in Operating Expenses was to cover required instrument calibration.

Project E Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$200,851	$10,500	$17,272	$14,500	$0	$28,615	**$271,738**
Actual Spent	$178,114	$3,893	$21,314	$5,000	$0	$25,211	**$233,532**
(Over)/Under Budget	**$22,737**	**$6,607**	**($4,042)**	**$9,500**	**$0**	**$3,404**	**$38,206**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$38,206**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to HR-delays in hiring and staff turnover.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is for purchases of necessary lab equipment.
- Underspent funds in Cooperative Agreements is due to funds obligated in FY22 that will be expended in FY23.

Project F Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$503,666	$15,283	$37,810	$0	$0	$68,626	**$625,385**
Actual Spent	$537,820	$13,728	$42,304	$0	$0	$73,198	**$667,051**
(Over)/Under Budget	**($34,154)**	**$1,555**	**($4,494)**	**$0**	**$0**	**($4,572)**	**($41,666)**
FY21 Unspent Funds	**$17,816**					**FY22 Unspent Funds**	**($23,850)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Overspent Salaries is due to promotions among staff and overtime associated with Bug Flow field studies and fall seining trip.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is for payments to community science participants and purchase of additional drift sampling equipment needed to provide JCM trips with their own gear for collection on trips.

Project G Budget

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$343,451	$4,000	$79,500	$520,766	$0	$68,249	**$1,015,966**
Actual Spent	$316,378	$1,731	$75,153	$520,766	$0	$64,097	**$978,126**
(Over)/Under Budget	**$27,073**	**$2,269**	**$4,347**	**$0**	**$0**	**$4,152**	**$37,840**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$37,840**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Underspent Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Underspent in Operating Expenses due to Pit Tags being purchased through BOR instead of the project.

Project H Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$181,222	$11,700	$25,566	$148,000	$0	$31,371	**$397,859**
Actual Spent	$123,423	$5,874	$68,077	$152,685	$0	$28,909	**$378,968**
(Over)/Under Budget	**$57,799**	**$5,826**	**($42,511)**	**($4,685)**	**$0**	**$2,462**	**$18,891**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$18,891**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Underspent Salaries is due to HR-delays in filling positions and staff turnover.
- Underspent in Travel & Training is due to Covid 19 impacts that limited or cancelled in person conferences.
- Overspent in Operating Expenses is due to change in funding mechanism for a cooperator from a Cooperative Agreement to a contract.
-Overspent amount in Cooperative Agreement is additional funds sent to USFWS for eDNA analysis.

Project I Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$233,790	$0	$12,100	$273,110	$0	$38,502	**$557,502**
Actual Spent	$272,402	$1,724	$18,141	$273,110	$0	$44,218	**$609,595**
(Over)/Under Budget	**($38,612)**	**($1,724)**	**($6,041)**	**$0**	**$0**	**($5,716)**	**($52,093)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($52,093)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Overspent Salaries is due to assignment of project staff reassigned back to the project to ensure completion of all project tasks outlined in the workplan.
-Overspent funds in travel and training is due to travel and training completed in FY22 that was rescheduled from FY21.
-Overspent funds in Operating Expenses is for purchases of necessary lab equipment and field supplies.

Project J Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$124,588	$3,000	$1,500	$45,500	$0	$17,276	**$191,864**
Actual Spent	$95,952	$5,874	$9,782	$69,000	$0	$15,827	**$196,435**
(Over)/Under Budget	**$28,636**	**($2,874)**	**($8,282)**	**($23,500)**	**$0**	**$1,449**	**($4,571)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($4,571)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 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 an international workshop organized by The Amazon Dams Network in Brazil.
- 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 12.326%	Total
Budgeted Amount	$372,175	$4,970	$3,400	$0	$0	$46,906	**$427,451**
Actual Spent	$275,035	$0	$11,342	$0	$0	$35,299	**$321,676**
(Over)/Under Budget	**$97,140**	**$4,970**	**($7,942)**	**$0**	**$0**	**$11,607**	**$105,775**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$105,775**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:

- Unspent Salaries is due to staff turnover in FY22 and HR-delays in hiring of a Database Administrator and a Geographer which will occur in FY23.
- Unspent Travel & Training money due to travel restrictions imposed by COVID-19 pandemic.

-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 12.326%	Total
Budgeted Amount	$164,641	$0	$0	$80,596	$0	$22,712	**$267,949**
Actual Spent	$153,144	$2,286	$11,482	$80,596	$0	$22,992	**$270,501**
(Over)/Under Budget	**$11,497**	**($2,286)**	**($11,482)**	**$0**	**$0**	**($280)**	**($2,552)**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**($2,552)**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:

-Underspent Salaries is due to staff turnover at the end of the fiscal year and change in mechanism for completing work.

-Overspent Travel & Training was for travel for a cooperator to the bi-ennial conference.

-Overspent in Operating Expenses is due to compensating contractors for data analysis.

Project M Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$690,221	$20,000	$178,000	$0	$0	$109,482	**$997,703**
Actual Spent	$535,988	$0	$194,321	$0	$0	$90,018	**$820,327**
(Over)/Under Budget	**$154,233**	**$20,000**	**($16,321)**	**$0**	**$0**	**$19,464**	**$177,376**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$177,376**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to staff turnover and HR delays in hiring the new GCMRC Chief.
- Underspent Travel & Training was due to travel restrictions and cancellations associated with COVID-19.
- Overspent funds in Operating Expenses is due to providing funds for shortfalls for project A and rising costs for vehicle maintenance and fuel.

Logistics Budget

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$269,502	$3,000	$1,074,767	$11,000	$0	$166,394	**$1,524,663**
Actual Spent	$216,046	$102	$1,237,597	$18,000	$0	$179,729	**$1,651,474**
(Over)/Under Budget	**$53,456**	**$2,898**	**($162,830)**	**($7,000)**	**$0**	**($13,335)**	**($126,811)**
FY21 Unspent Funds	**$131,070**					**FY22 Unspent Funds**	**$4,259**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Underspent Salaries is due to change in staff and crediting warehouse staff hours for tribal and stakeholder river trips.
- Underspent funds for Travel & Training were due to travel restrictions associated with COVID-19.
- Overspent funds in Operating Expenses is due to the rescheduled Channel Mapping river trip from project B from FY21 that was completed in FY22.
- 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 12.326%	Total
Budgeted Amount	$16,180	$1,500	$2,500	$0	$0	$2,487	**$22,667**
Actual Spent	$18,314	$0	$0	$0	$0	$2,257	**$20,571**
(Over)/Under Budget	**($2,134)**	**$1,500**	**$2,500**	**$0**	**$0**	**$230**	**$2,096**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$2,096**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
-Overspending Salaries is due to higher employee salary costs.
-Underspent Travel & Training is due to cancellations assocaited with COVID-19.
-Underspent funds in Operating Expenses was for software that was provided by USGS licensing at no cost to the project.

Project O Budget

Project O	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 12.326%	Total
Budgeted Amount	$230,993	$12,000	$5,000	$25,885	$40,667	$31,344	**$345,889**
Actual Spent	$50,443	$1,411	$25,047	$168,500	$0	$14,534	**$259,935**
(Over)/Under Budget	**$180,550**	**$10,589**	**($20,047)**	**($142,615)**	**$40,667**	**$16,810**	**$85,954**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$85,954**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Project O is entirely funded through FY21 unspent funds.
- Underspent Salaries were covered by USGS employees as well as through CESU cooperative agreements with Oregan State University and Utah State University.
-Overspent Operating Expenses is a contract with Marda Science for Riverbed Vegetation mapping awarded in FY22 instead of FY21.
-Overspent amount in Cooperative Agreement is due to change in mechanism for completing work through CESU cooperative agreements.

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 12.326%	Total
Budgeted Amount	$4,316,729	$103,493	$1,527,286	$1,554,102	$392,587	$779,713	**$8,673,910**
Actual Spent	$3,998,805	$51,678	$1,836,953	$1,236,254	$459,407	$762,773	**$8,345,871**
(Over)/Under Budget	$317,924	$51,815	($309,667)	$317,848	($66,820)	**$16,940**	**$328,039**
FY21 Unspent Funds	**$0**					**FY22 Unspent Funds**	**$611,924**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- Actual unspent total balance will be used to cover planned budget shortfalls and unfunded work in FY23 and FY24.

Appendix 1 Budget

Lake Powell (NOT GCDAMP funded)							
	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 20.163%	Total
Budgeted Amount	$145,065	$8,814	$11,968	$0	$0	$33,440	**$199,287**
Actual Spent	$188,290	$5,699	$24,507	$0	$0	$44,055	**$262,551**
(Over)/Under Budget	**($43,225)**	**$3,115**	**($12,539)**	**$0**	**$0**	**($10,615)**	**($63,264)**
Unspent Funds	**$63,264**					**2022 Unspent Funds**	**$0**

COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*

FY22 Comments:
- This project is funded entirely by Reclamation with non-GCDAMP funding.
- This agreeemnt period of performance ended 12/31/2022 and shows all funding expended through the calendar year.
- Overspent Salaries is due to this agreement being on the calendar year rather than the fiscal year and actual salary overspending is between 9/30/22 and 12/31/2022 when the agreement ended.
- Underspent Travel & Training were due to travel restrictions associated with COVID-19.
-Overspent Operating Expenses is for a Sonde and equipment purchase that was made after the fiscal year.
-All funds have been expended at the end of the calendar year and a new 5 year agreeement start date is 1/1/2023-12/31/2027