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

Fiscal Year 2020
Annual Project Report
to the
Glen Canyon Dam
Adaptive Management Program

Prepared by

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Introduction

Following is the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center's (GCMRC) Fiscal Year (FY) 2020 Annual Accomplishment Report. This report is prepared primarily for the Bureau of Reclamation to account for work conducted and products delivered in FY 2020 by GCMRC and to inform the Technical Work Group of science conducted by GCMRC and its cooperators in support of the Glen Canyon Dam Adaptive Management Program (GCDAMP).

It includes a summary of accomplishments, modifications, results, and recommendations related to projects included in GCMRC's FY 2018-20 Triennial Work Plan (U.S. Department of the Interior [US DOI], 2017) for FY 2020 or, in some cases, for the entire period of the TWP[1]. This work was done to support the 11 resource goals identified in the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement and Record of Decision (US DOI, 2016; Table 1). The FY 2020 Report contains changes based on recommendations from the Bureau of Reclamation. These include the addition of the LTEMP Project elements table (Table 2) from the FY 2018-20 TWP that identifies GCMRC's work toward addressing LTEMP Resource Goals relative to LTEMP dam operations and experimental actions (p. 68 of the FY 2018-20 TWP). Also, the Deliverables (Products) have been moved to the end of the report (Appendix 2) and project budgets are listed in each project and compiled together as Appendix 3.

References

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

U.S. Department of the Interior, 2017, Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2018-2020—Final submitted to the Secretary of the Interior: Flagstaff, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center and Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 316 p., https://www.usbr.gov/uc/progact/amp/amwg/2017-09-20-amwg-meeting/Attach_04a.pdf. (Scroll to pg. 10 for the beginning of the Work Plan.)

[1] 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. The use of trade names is for informational purposes only and does not imply endorsement.

Table 1: LTEMP Resource Goals

Archaeological and Cultural Resources

LTEMP Resource Goal	Project Addressing this Goal
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.	This LTEMP resource goal is being addressed by Project D through examining how flow and non-flow actions will ultimately affect the long-term preservation of cultural resources and other culturally-valued and ecologically important landscape elements located within the Colorado River ecosystem (CRe).

Natural Processes

LTEMP Resource Goal	Project Addressing this Goal
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.	This LTEMP resource goal is being 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 Addressing this Goal
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.	This LTEMP resource goal is being 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 (LCR) and within the LCR, 4) monitoring the status and trends of native and nonnative fishes that occur in the CRe from Lees Ferry, AZ 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 Addressing this Goal
Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.	This LTEMP resource goal is being 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 Addressing this Goal
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.	This LTEMP resource goal is being 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 nutrients that control the abundance and growth of the trout population.

Other Native Fish

LTEMP Resource Goal	Project Addressing this Goal
Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.	This LTEMP resource goal is being 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 LCR and within the LCR, and 4) monitoring the status and trends of native and nonnative fishes that occur in the Colorado River ecosystem from Lees Ferry to Lake Mead.

Sediment

LTEMP Resource Goal	Project Addressing this Goal
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.	This LTEMP resource goal is being 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 Addressing this Goal
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.	This LTEMP resource goal is being 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 Addressing this Goal
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.	This LTEMP resource goal is being 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 nutrients 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 LCR and within the LCR.

Nonnative Invasive Species

LTEMP Resource Goal	Project Addressing this Goal
Minimize or reduce the presence and expansion of aquatic nonnative invasive species.	This LTEMP resource goal is being 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 fishes 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 LCR and within the LCR, 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 Addressing this Goal
Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.	This LTEMP resource goal is being 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 2018-20 Triennial Work Plan

Project elements in the FY 2018-20 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 and cultural resources	Natural Processes	Humpback chub	Hydropower and 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.1/A.2 C.1/C.2 E.1/E.2 F.1/F.3/F.4 Appendix 1	E.1/E.2 F.2 G.1/G.2/G.3/ G.4/G.5/G.6/G. 9 I.1/J.2	N.1	E.1/E.2 F.2 G.9 I.1	B.1/B.2/ B.4 H.1	A.1/A.3 B.1/B.2	J.1	E.1/E.2 F.4 G.9 H.4 I.1	F.5 I.1/I.2/I.3 G.9 J.2	C.1/C.2
Fall High-Flow Experiments (HFE) > 96-hr ≤ 45,000 ft^3/s, in Oct. or Nov.	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Fall HFE ≤ 96-hr ≤ 45,000 ft^3/s, in Oct. or Nov.	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Humpback chub translocation			G.1/G.7/G.8							G.7/G.8	
Larval humpback chub head-start program			G.1								
Macroinvertebrate production flows ("Bug Flows")		F.3	F.1/F.2/F.4	N.1	F.1/F.2/F.4				F.1/F.4 H.1/H.2/H.3	I.1	
Mechanical removal of invasive fish			I.1/I.2							I.1	
Mechanical removal of rainbow trout from LCR reach			I.1/J.2		I.2					J.2	
Proactive spring HFE ≤ 45,000 ft^3/s, in April, May or June	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Riparian vegetation restoration	D.1	C.3/C.4				C.3/C.4				C.3/C.4	C.1/C.2/C.3 /C.4
Spring HFE ≤ 45,000 ft^3/s, in March or April	D.1	C.1/C.2/C.3	A.2 F.1/F.2	N.1	F.1/F.2	B.1	A.1/A.3 B.1/B.2/B.4		A.2 F.4 H.1/H.2/H.3		C.1/C.2/C.3
Trout management flows		C.1/C.2/C.3	J.2	J.2 N.1					H.1/H.2/H.3	F.5 J.2	C.1/C.2/C.3

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

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Summary

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

Goals and Objectives

The Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem Project is focused on high-resolution monitoring 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. The data collected by this project are used to inform managers on 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 stage, discharge, and water-quality data collected by this project support the following nine LTEMP goals: aquatic food base, archaeological and cultural resources, humpback chub, hydropower and energy, invasive fish species, natural processes, rainbow trout fishery, recreational experience, and riparian vegetation. Details of this ongoing project (including descriptions of the data collection locations) are provided in the GCMRC Fiscal Years (FY) 2018–20 Triennial Work Plan.

Science Questions Addressed & Results

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

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

These hypotheses are paraphrased from the LTEMP EIS and from earlier goals, information needs, and strategic science questions formulated by the Glen Canyon Dam Adaptive Management Program.

The results from Project A during FY 2018-20 are provided in the 12 presentations made at professional scientific meetings, 6 journal articles, 2 USGS reports, 1 USGS data release, and 2 web applications described in the Deliverables list. All monitoring data collected by this project, including those required to trigger, design, and evaluate the November 2018 HFE, were collected and posted to the project web application (https://www.gcmrc.gov/discharge_qw_sediment/). Processing of all data is complete and all data have been uploaded to and are available at this website, except for laboratory analyses of some of the suspended-sediment data from automatic pump samplers (this task will be completed by the end of February 2021, as is the usual schedule for this project). Given the multifaceted nature of Project A, only a few key results are listed herein.

- 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. Sand erodes during years of below-average to average tributary sand supply and higher discharge; at least 28 million metric tons of sand have likely been eroded from the Colorado River in Grand Canyon National Park since the 1963 closure of Glen Canyon Dam. Thus, 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, *in press*).

- Sand storage in the bedrock-canyon Colorado River in Marble and Grand Canyons is largely self-limiting. Fining of the bed-sand grain size as sand storage increases leads to higher suspended-sand concentrations, and therefore greater downstream sand export, a negative-feedback mechanism likely in other bedrock-canyon rivers. By virtue of this self-limitation, substantial increases in sand storage, as occurred during periods of low discharge pre-dam, are likely impossible in the Colorado River in Marble and Grand Canyons at the higher discharges generally released from Glen Canyon Dam (Topping and others, *in press*).
- Sand supplied during tributary floods migrates downstream in the Colorado River as a sand wave. The front of this wave migrates downstream at nearly the velocity of water, with some newly supplied sand in this packet never being retained in the CRe. The lagging part of this wave migrates more slowly and takes hundreds of days to be exported to Lake Mead (Topping and others, *in press*).
- The bed-sand fining caused by sand-wave migration persists for <63 days in Upper Marble Canyon and <144 days in Lower Marble Canyon. Thus, only those HFEs released within several months of a large Paria River flood will have access to the finest sand size classes that lead the highest suspended-sand concentrations, and hence the largest sandbar-deposition rates in Marble Canyon (Topping and others, *in press*).
- The sand supply from the Little Colorado River to the CRe has decreased substantially since the 1960s, and this decrease is ongoing. This decrease in sand transport owes to biogeomorphic feedbacks initiated by vegetation colonization of the channel of the Little Colorado River during periods lacking large floods, thereby trapping sand, causing channel narrowing, causing greater attenuation of flood peaks, and thus leading to additional vegetation encroachment. This process has been exacerbated by progressive upstream water development in the Little Colorado River Basin. Thus, as a result of the biogeomorphic feedbacks and upstream water development, flood peaks have decreased substantially over time in Little Colorado River (Dean and Topping, 2019). The chief management ramification of the decrease in the Little Colorado River sand supply is that sustainable sand management is made more difficult in the CRe for the reasons mentioned in the previous bullets.
- The progressive decrease in flood peaks in the Little Colorado River has greatly reduced the magnitude and frequency of geomorphic disturbance in the lowermost Little Colorado River, that is, the reach that provides critical habitat for the endangered humpback chub (*Gila cypha*). This loss of disturbance has already

caused and is forecast to cause greater aggradation of travertine dams, infilling of pools with sediment, and greater encrustation of clean gravels with travertine (Unema and others, *in press*).

- The combined mean-annual sand supply from the lesser tributaries in Upper Marble Canyon is 10% of that from the Paria River (Griffiths and Topping, 2017). During rare periods, the combined sand supply from these tributaries can, however, exceed that of the Paria River For example, during summer 2000, House Rock Wash supplied 53,000 metric tons of sand to the Colorado River while the Paria River supplied only 3,500 metric tons of sand (http://www.gcmrc.gov/discharge_qw_sediment/).
- During FY 2018-20, the following changes in sand mass (shown in tabular form) occurred in the six reaches where continuous mass-balance sand budgets are constructed by Project A. Among the reaches upstream from Diamond Creek that did not have indeterminate annual sand budgets, 1.1±0.2 million metric tons of sand were eroded and 0.73±0.28 million metric tons of sand were deposited during FY 2018-20. Most of the erosion occurred in the upstream part of the CRe (Upper Marble Canyon) whereas much of the deposition occurred in the downstream part of the CRe between National Canyon and Diamond Creek (West-Central Grand Canyon). Thus, dam operations interacted with the tributary sand supply to cause a net transfer of sand from Marble Canyon to the downstream part of Grand Canyon and the Lake Mead Delta during FY 2018-20. Data from (http://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP).

Reach	Change in sand mass in metric tons during each fiscal year; interpretation of change in bold uses criteria in Topping and others (*in press*)		
	2018	2019	2020
Upper Marble Canyon	54,000±140,000 **Indeterminate**	-530,000±120,000 **Erosion**	-210,000±48,000 **Erosion**
Lower Marble Canyon	110,000±86,000 **Deposition**	17,000±110,000 **Indeterminate**	13,000±32,000 **Indeterminate**
Eastern Grand Canyon	-51,000±120,000 **Indeterminate**	44,000±270,000 **Indeterminate**	-70,000±100,000 **Likely Erosion**
East-Central Grand Canyon	280,000±170,000 **Deposition**	46,000±220,000 **Indeterminate**	-87,000±67,000* **Erosion**
West-Central Grand Canyon	-180,000±150,000 **Erosion**	200,000±200,000 **Deposition**	140,000±62,000* **Deposition**
Western Grand Canyon and the Lake Mead Delta (that is, the Colorado River downstream from Diamond Creek)	1,100,000±56,000 **Deposition**	1,900,000±93,000 **Deposition**	560,000±28,000* **Deposition**
*Data used to compute these values end in late August 2020 because the Colorado River above National Canyon near Supai, AZ, and the Colorado River above Diamond Creek near Peach Springs, AZ, gaging stations had not been visited since August 25 and 27, respectively, at the time this report was completed.			

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Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$561,750	$10,400	$72,600	$0	$426,600	$88,937	**$1,160,287**
Actual Spent	$623,234	$2,341	$46,747	$0	$388,543	$92,740	**$1,153,605**
(Over)/Under Budget	**($61,484)**	**$8,059**	**$25,853**	**$0**	**$38,057**	**($3,803)**	**$6,682**
FY19 Carryover	**$0**					**FY20 Carryover**	**$6,682**

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

- Higher costs for salary were due to the need for increased overtime as a result of back log of processing of samples from previous years.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.
- Lower costs in funding to other USGS Centers was due to additional funding being allocated in FY2019 for additional discharge work and database programming which was necessary to fully inform suspended sediment concentrations and budgets.

Project B: Sandbar and Sediment Storage Monitoring and Research

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Summary

The five sand-enriched high-flow experiments (HFEs) that have occurred since 2012 have resulted in increases in sandbar volume for most bar types. Most of the sand in the HFE deposits originates from the Paria River, however up to 25% may be relict pre-dam sand, based on the findings from a recently completed study on the geochemical composition of sandbars. While observations demonstrate that HFEs benefit campsites and cause temporary increases in campsite area, vegetation encroachment continues to cause progressive declines in campsite area at some locations. Repeat measurements of sand storage in eddies and the riverbed has demonstrated that sand accumulation can occur over periods that include substantial inputs of sand from the Paria River and average or lower dam-release volumes, which has occurred for some periods between 2012 and 2020. Net erosion results when dam-release volumes are above average, which occurred in 2011.

Below, we describe Project B activities that occurred in FY 2020 and summarize the major results from the three-year work plan that are described in greater detail in the referenced deliverables and publications. The list of deliverables at the end of this report is cumulative for the Fiscal Years (FY) 2018-20 work plan and includes three recurring data products, five publications completed in FY 2020 and 13 publications that were completed in FY 2018 and 2019. In addition to those publications, there were six data releases and several additional presentations and/or proceedings publications.

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 and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics. This project addresses Long-Term Experimental and Management (LTEMP; US DOI, 2016) resource goals for sediment by measurements of sandbars and sand storage in the river channel and by contributing to the development of predictive tools for sand transport and sandbar behavior. This project also contributes to goals for recreational experience by measurements of campsite area and evaluation of campsites by the citizen science Adopt-a-Beach program. Outcomes from this project will be used to evaluate the effectiveness of the HFE protocol included in the 2016 Record of Decision with respect to sandbar condition.

Science Questions Addressed and Results

B.1. Sandbar Monitoring Using Topographic Surveys and Remote Cameras

Project Element B.1 addresses the hypothesis that sand-enriched HFEs will continue to result in deposition of sand thereby improving condition at sandbars and campsites. This science question is addressed through annual monitoring with topographic surveys, analysis of images from remote cameras, and advances in data management.

Sandbar Monitoring and Response to High-Flow Experiments

Sandbar and campsite monitoring data were collected in October 2019, processed, and reported at the Annual Reporting Meeting in January 2020. Monitoring data were recently collected in October 2020; and those data are currently being processed and will be presented at the Annual Reporting Meeting in January 2021. Images from the remote cameras were retrieved in October 2019, February 2020, and October 2020. The citizen science Adopt-a-Beach program was continued by the Grand Canyon River Guides, although fewer observations were made in Summer 2020 owing to the COVID-19 pandemic.

To date, five HFEs have been conducted under sand-enriched conditions since the HFE Protocol was initiated in 2012. Those HFEs occurred in November each year in 2012, 2013, 2014, 2016, and 2018. In each case, sandbar building results were consistent with the results from previous HFEs (Grams, 2019). All HFEs resulted in substantial deposition at all sandbar types (see Mueller and others, 2018 for description of sandbar types). New findings from a recently completed study on the geochemical composition of HFE-deposited sand demonstrates that the HFE deposits in Marble Canyon are composed primarily of sand derived from the Paria River (Chapman and others, 2020). The predominance of Paria-derived sand in the HFE deposits indicates the HFEs are functioning as intended in the HFE Protocol. However, up to 25% or more of the sand in HFE deposits is likely relict from the pre-dam period, indicating that pre-dam sand is still a substantial component of the sand storage in Marble Canyon and subject to erosion and downstream transport (Chapman and others, 2020).

HFE deposition was followed by erosion of about half the new deposition within six months, which is also consistent with the response to previous HFEs (Grams, 2019). The sandbar measurements indicate that there has been some net increase in the size of reattachment sandbars since the beginning of the HFE protocol in 2012 (Figure 1). The size of other types (Mueller and others, 2018) of sandbars has fluctuated, with no significant net increase or decrease. Thus, despite erosion of much of the HFE-deposited sand, the deposits do persist longer at some sites. Deposition of sand during HFEs has caused temporary increases in campsite area; however, there has been a net long-term decline in campsite area caused by vegetation encroachment (Hadley and others, 2018a; 2018b). Although vegetation encroachment causes reductions in campsite area (Hadley and others, 2018b), it also promotes deposition and sand retention as described in a recently completed study by Butterfield and others (2020). In summary, HFEs do not prevent vegetation encroachment; however, HFEs do provide increases in campsite area—even if those increases are temporary.

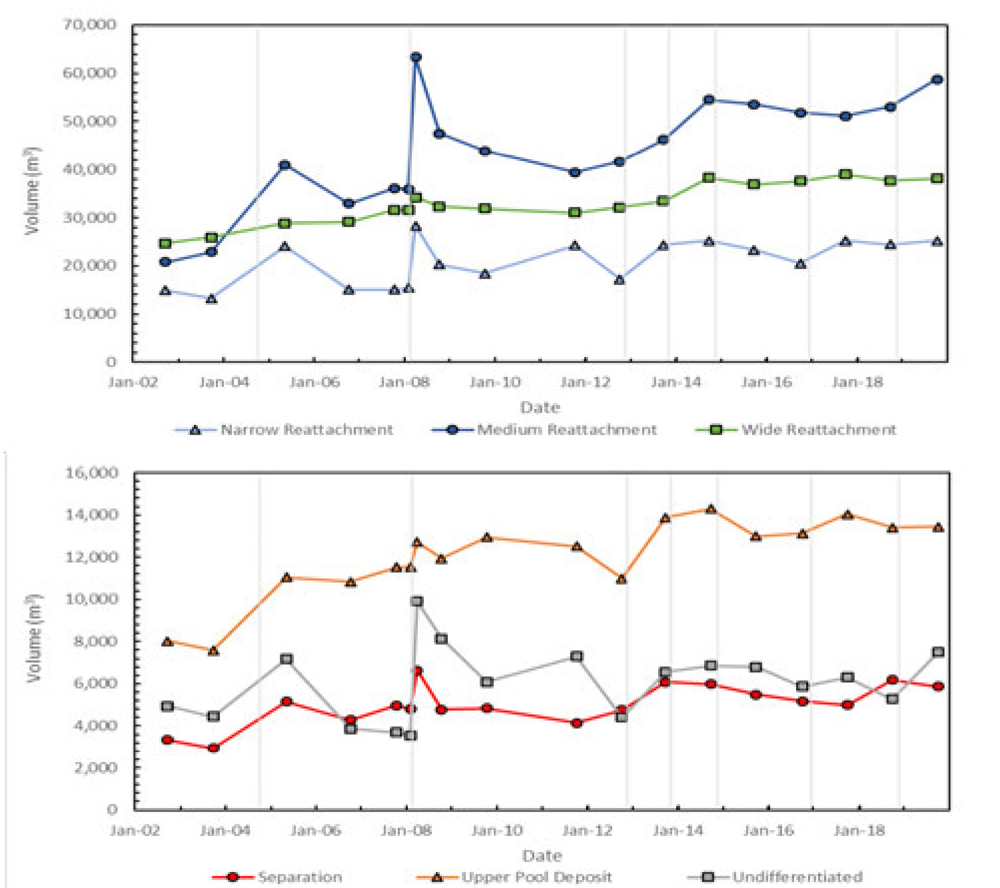

Figure 1. Sandbar volume (m^3) at long-term monitoring sites along the Colorado River in Grand Canyon National Park, Arizona by sandbar type from 1990 through October 2019. Group 1a, 1b, and 1c are unvegetated, moderately vegetated and heavily vegetated reattachment bars, respectively (Mueller and others, 2018). Group 2 sites are separation bars in high-energy, wave-dominated eddies. Group 3 sites are vegetated upper-pool sandbars. Group 4 sites are separation bars in low-energy eddies. Solid vertical lines are High-Flow Experiments of 36,000 ft^3/s or greater. Modified from Mueller and others (2018).

Analysis of Remote Camera Images

The images collected by remote cameras are used to evaluate the effects of the HFEs on the sandbar monitoring sites (Grams and others, 2018b; Grams, 2019). During implementation of the FY 2018-20 work plan, a workflow was developed for testing, training, and validating Deep Convolutional Neural Networks, a type of Machine Learning, capable of automatically detecting (segmenting) sandbars in remote camera imagery (Grams and others, 2018b; Buscombe and Ritchie, 2018; Lima and others, 2019). A manuscript comparing different network architectures and their accuracy in detecting sandbars in oblique imagery is currently in review. Progress has been made in developing new tools to use measurements from the segmented imagery to measure changes in sandbar area at multiple elevations, to quantify changes in elevational storage of sand before and after HFEs, and to identify metrics which can be correlated with annual measurements of sandbar volume. We are currently in the process of implementing these methods to produce a monthly time-series of sandbar change at a subset of the sandbar monitoring sites to enable better quantification of the short-term changes in sandbars, such as the amount of deposition that occurs during HFEs and sandbar mass failure events that have been observed in association with changes in dam operations.

Developments in Sandbar Data Processing and Public Database

FY 2020 was the third year of implementing a new workflow and database for processing, analyzing, storing, and disseminating the sandbar monitoring data. The workflow is standardized and allows automated processing of the entire data set and is implemented in a "workbench" that is based on open-source processing tools. The processing outputs of the workbench are stored in a MySQL database that powers the public-facing sandbar webpage where the data can be accessed and visualized by the public (www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/). In 2020, changes in USGS internet security protocols have required changes to the webpage programming, which are currently in progress. Until these changes are complete, the webpages may be inaccessible. The database stores the results of over 1,800 individual topographic and bathymetric surveys that have been completed at 45 long-term monitoring sites.

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

Project Element 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 science question is addressed through periodic monitoring of sandbars and the riverbed with coupled topographic and bathymetric surveys and research efforts to improve methods for riverbed characterization and bedload sand transport.

Long-term Trends in Sandbars and Sand Storage

Data were collected to map changes in riverbed sand storage in Lower Marble Canyon and Eastern Grand Canyon in FY 2019. No additional data collection was planned for FY 2020. Processing of data collected in FY 2019 was slightly delayed to ensure work environment safety during the COVID-19 pandemic, but processing is now nearly complete and preliminary results are expected to be presented at the January 2021 reporting meeting.

Grams and others (2018a) reported on repeat mapping of the riverbed in Lower Marble Canyon and demonstrated that repeat mapping of at least 50% of the river segment was required to determine the sand budget with signal-to-noise ratio (SNR) > 1. These findings mean that the repeat maps that have been collected beginning in 2009 will be both sufficient and necessary to determine long-term trends in sandbars and sand storage in eddies and the channel throughout Grand Canyon. This analysis was for the 2009 to 2012 period, which did not include HFEs, but did include sustained high-flow volumes in 2011 for reservoir equalization. These flows resulted in sand evacuation that was temporally concentrated (~100% of mass change occurred during 19% of the study period) and highly localized (70% of mass change occurred in 12% of the study segment). Analyses of additional data sets show sand evacuation in Eastern Grand Canyon between 2011 and 2014 and sand accumulation in Upper Marble Canyon between 2013 and 2016. Together, these results demonstrate that sand accumulation can occur over periods that include substantial inputs from the Paria River and average or lower dam-release volumes (annual volumes were less than 9.2 million acre-feet every year between 2013 and 2016). Net erosion occurs when dam-release volumes are above average (the 2011 annual volume was 12.7 million acre-feet).

Advances in Bedload Sediment Transport and Bed Sediment Classification

During the FY 2018-20 work plan, several manuscripts were published on the topics of bedload and suspended sediment transport in Grand Canyon. The papers have examined different aspects of the problems of data processing, collection and modeling of sediment transport. Three studies have made extensive use of a unique dataset collected upstream from the Diamond Creek gage (USGS gage 09404200 at river mile 225) between 2015 and 2019. This dataset consists of repeat measurements of a ~300-m long segment of the riverbed made at ~10-minute intervals over ~10-hour periods for several different flow conditions. These measurements track the migration of dunes on the riverbed and can be used to model the rate of sand transport along the riverbed. Leary and Buscombe (2019) used this dataset to demonstrate that estimates of bedload transport based on less extensive time-series of bed elevation changes at a point (i.e. from a singlebeam sonar) introduce unacceptable error due to the ambiguity of migrating dune length and period. Ashley and others (2019) used the dataset to develop a Bayesian framework for estimating bedload transport at each long-term sediment monitoring gage. The new model, based on previously developed theory, continuously predicts bedload based on available suspended sediment, discharge and grain size information at gages only, with well-defined uncertainties. The application of the model might also be useful for identifying periods of relative sediment deficit and surplus in reach-scale sediment storage, which will be tested in future studies. Finally, Guala and others (2020) used the bedform dataset to develop a new model for predicting bedload flux based on dune geometry and bed shear stress. This model enables estimates of bedload for any reach within Grand Canyon given bedform geometry estimates, depth and water surface slope measurements, all of which are derived products from channel mapping bathymetric and topographic data.

Making use of a different long-term dataset, Rubin and others (2020) analyzed the large set of bed sand grain size, suspended sand grain size, and suspended sand concentration measurements that have been collected since 2000. This analysis demonstrates the large variability in suspended sand concentration that occurs in the Colorado River that is independent of discharge and not predicted by changes in sand grain size. These findings have implications for the development of accurate models for sand transport that are used to design HFEs and predict sandbar response to dam operations.

The data collected during the channel mapping efforts are also used to map and classify the bed sediment composition. During the FY 2018-20 work plan, methods for classifying bed sediment more accurately using multi-spectral acoustics were developed and evaluated (Buscombe and Grams, 2018). Additionally, methods for bed texture classification with recreational-grade sonar instruments were developed by Hamill and others (2018).

B.3. Control Network and Survey Support

The B.3 Project Element 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 datasets.

The FY 2020 operations to expand survey control into previously unsurveyed reaches of West Central Grand Canyon (river mile 88 to 166) for channel mapping were deferred until April 2021. Work on the control network in that reach is essential to prepare for mapping the sandbars and riverbed in that reach, which is proposed for the FY 2021-23 work plan. The existing control network has been imported and redeveloped in updated software applications so adjustments can be performed in 64-bit operating systems.

Terrestrial and GPS control measurements collected for the past 30 years have been combined into a single database for accuracy assessments and future least-squares adjustments. The Survey Support project has provided survey and geodetic support for the following projects:

- Little Colorado River historical channel changes
- National Park Service airborne lidar mission
- GCMRC Terrestrial lidar mission
- USGS Arizona Water Science Center Gravity measurements along Highway 64 and Grand Canyon's South Rim
- Reclamation study of paleo flood deposits

GCMRC has been working alongside the National Geodetic Survey to ensure the decades of spatial data collected within the Grand Canyon region can be seamlessly combined with future datasets. The North American Datum of 1983 (NAD83) will be superseded with the North American Terrestrial Reference Frame of 2022 (NATRF2022). This migration will require new horizontal and vertical coordinates to be computed which will take into account 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. The regional geodetic improvements which improve monitoring and research capabilities include:

- Grand Canyon's Low-distortion, State Plane Projection Systems have been approved by the National Geodetic Survey for incorporation into the North American Terrestrial Reference Frame of 2022 (NATRF2022).
- Special Use Zones developed for Reclamation water storage projects have been proposed to the National Geodetic Survey for incorporation into NATRF2022 and are awaiting final approval.
- Airborne Gravity data though the Grav-D project has been collected and processed and is available for the Grand Canyon Region. This data has been used in the most recent Geoid model (Geoid18) and will provide much more accurate GPS derived elevations. These data are particularly helpful in this region due to lack of differential leveling networks to the Colorado River.

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Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$477,421	$5,900	$27,000	$374,126	$0	$81,617	**$966,064**
Actual Spent	$325,273	$5,101	$21,881	$816,763	$0	$73,093	**$1,242,111**
(Over)/Under Budget	**$152,148**	**$799**	**$5,119**	**($442,638)**	**$0**	**$8,524**	**($276,048)**
FY19 Carryover	**$392,821**					FY20 Carryover	**$116,773**

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

- Lower costs in salary was due to a vacancy. This work was accomplished through cooperative agreements.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.
- Higher costs in cooperative agreements was due to additional funding to conduct work associated with a vacancy at GCMRC and the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project C: Riparian Vegetation Monitoring and Research

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Summary

Riparian vegetation is an important part of the Colorado River Ecosystem (CRe) in that it influences sediment deposition and retention, is key habitat for wildlife, can reduce camping area, adds beauty to the landscape, and creates shade and windbreaks. This project aims to monitor changes to riparian vegetation using field-collected data and digital imagery (C.1, C.2), develop predictive models of vegetation composition as it relates to hydrological regime (C.3), and provide monitoring protocols and decision support tools for active vegetation management (C.4).

Goals and Objectives

The list of accomplishments and deliverables listed is cumulative for the Triennial Work Plan FY 2018-2020. Products completed during this timeframe are included in the "Deliverables" list (Appendix 2). Results of both completed and on-going work initiated in FY 2018-2020 are described in "Science Questions Addressed & Results."

Science Questions Addressed & Results

C.1. Ground-based Vegetation Monitoring

In this Project Element, we conduct annual ground-based vegetation monitoring to assess the status (composition and cover) of native and nonnative vascular plant species within the riparian zone of the Colorado River from Glen Canyon Dam (GCD) to 240 river miles downstream of Lees Ferry. Over longer time frames, this Element also examines changes in the vegetation composition and cover of the riparian zone, as related to geomorphic setting and dam operations.

Riparian vegetation monitoring data were collected at sites between river miles (RM) -15.5 and 240 in August, September, and October in 2018, 2019, and 2020. Data were collected at randomly selected sandbars, debris fans, and channel margins, and at the long-term monitoring sandbars included in Project B. The number of sites sampled varied by year with 99, 106, and 96 randomly selected sites and 43, 42, and 45 long-term sites sampled in 2018, 2019, and 2020, respectively. All vegetation monitoring data collected under C.1 are now stored in a new database specifically designed as a part of Project K for the long-term maintenance and dissemination of these data. The 2020 data are currently being entered and error checked. Data collected from 2014 through 2019 are being analyzed for patterns and trends (for example, Figure 1). This analysis is currently being prepared as a USGS Status and Trends report (Butterfield and others, *in prep*).

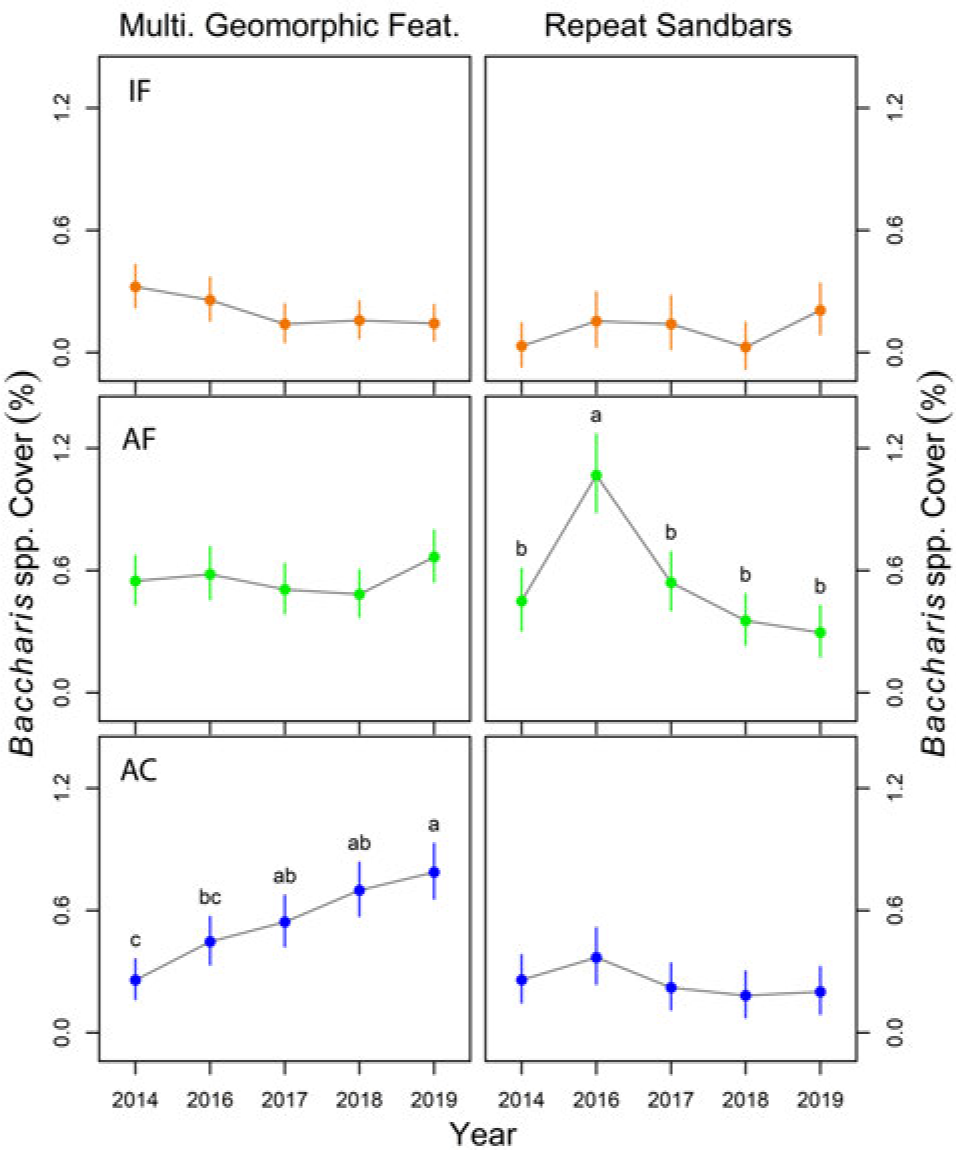

Figure 1. Fitted model estimates for Baccharis species cover across hydrological zones (IF, inactive floodplain – orange; AF, active floodplain – green; AC, active channel – blue). Different lowercase letters indicate significant differences at α = 0.05 based on Tukey's post-hoc comparisons. This is one example of many analyses being conducted as part of a forthcoming Status and Trends report.

The riparian vegetation monitoring protocol developed to meet the goals of Project C.1 was published as a USGS Techniques and Methods document in 2018 (Palmquist and others, 2018b). This peer-reviewed document includes detailed standard operating procedures in order to make these methods transparent and reproducible over time.

Two journal articles were published in 2018 that were conducted in support of developing reliable vegetation monitoring methods. The first used data from the 2014 randomly selected sites to evaluate differences in riparian floristic composition in the CRe (Palmquist and others, 2018a). This research identified three unique floristic groups that occur between Glen Canyon Dam and Lake Mead related to temperature and precipitation differences and may respond differently to dam operations. The second is an assessment of the strengths and weaknesses of two main methods for sampling vegetation, ocular cover estimates and line-point intercept (Palmquist and others, 2019). This comparison was conducted in Glen Canyon below Glen Canyon Dam specifically to determine how these methods perform in the complex, multilayered vegetation along the Colorado River.

A USGS-hosted website describing riparian vegetation research in Grand Canyon was made available during FY 2018 and is regularly updated: https://www.usgs.gov/centers/sbsc/science/overview-riparian-vegetation-grand-canyon?qt-science_center_objects=0#qt-science_center_objects. It discusses the importance of riparian vegetation in Grand Canyon and provides links to information on current research and monitoring activities and publications.

C.2. Imagery-based Riparian Vegetation Monitoring at the Landscape Scale

In work completed prior to the FY 2018-20 work plan, landscape-scale remote sensing of riparian vegetation was successfully used by GCMRC scientists to investigate several important contemporary environmental issues related to dam operations in the CRe. Specifically, we: 1) quantified long-term changes in total riparian vegetation related to dam release patterns (discharge from the dam) and regional climate within specific reaches of the CRe (Sankey and others, 2015a), 2) classified and mapped the composition of riparian vegetation of the CRe (Durning and others, 2018; Ralston and others, 2008; Sankey and others, 2015b), and 3) mapped nonnative invasive tamarisk vegetation impacted by the introduced tamarisk beetle using 2009 and 2013 imagery from Glen Canyon Dam to Lake Mead and 2013 airborne lidar (Bedford and others, 2017; Sankey and others, 2016).

In the first year (FY 2018) of the FY 2018-20 work plan, we finalized several additional remote sensing derived datasets and publications on the riparian zone of the Colorado River in Grand Canyon: Bedford and others (2018), Kasprak and others (2018), and Sankey and others (2018). During the remainder of the FY 2018-20 work plan, we leveraged those datasets and studies described above to address the following research and monitoring objectives:

- C.2.1. *Analyze mapped species and associations to determine how the composition of woody riparian vegetation varies spatially throughout the entire river corridor and how species have changed through time as captured in digital imagery;*
- C.2.2. *Quantify where, and to what degree, the combination of riparian vegetation encroachment and flow regime changes have altered bare sand area, and map turnover between riparian vegetation and bare sand due to erosion, deposition, establishment, and mortality;*
- C.2.3. *Detect where tamarisk beetle herbivory events and tamarisk mortality have occurred since 2013.*

Below we report on progress made during the FY 2018-20 work plan to address each of the research and monitoring objectives.

With respect to objective C.2.1, we finalized our map (see Figure 2 for an example) of riparian vegetation by species from Glen Canyon Dam to Lake Mead based on the 2013 overflight imagery (Durning and others, 2016) and published this as a USGS data release (Durning and others, 2018).

With respect to objective C.2.2, in 2018 we published our map of unvegetated, bare sand (Sankey and others, 2018) in the riparian zone from Glen Canyon Dam to Lake Mead based on the 2013 overflight imagery (Durning and others, 2016). In FY 2019, we analyzed the Durning and others (2018) and Sankey and others (2018) datasets and used flow scenario modeling in collaboration with Project Element C.3 to address the questions posed by objectives C.2.1 and C.2.2 (Figure 3). We have two different journal articles that are deliverables detailing the results of these analyses; one article is published (Kasprak and others, *in press*; Figure 4) and the other is in review (Durning and others, *in review*). We also have presented the results of these analyses in several conference presentations.

With respect to objective C.2.3, in 2017 and 2018 we published a map dataset (Bedford and others, 2017) and a manuscript (Bedford and others, 2018) describing tamarisk beetle impacts to tamarisk vegetation in the riparian zone of the river from Glen Canyon Dam to Lake Mead based on overflight remote sensing imagery acquired in 2009 and 2013. Those products were both final deliverables of the FY 2015-17 work plan. In FY 2018, we began using those datasets in conjunction with analysis of new, more recent satellite imagery acquired since 2013 to detect where tamarisk beetle herbivory events and tamarisk mortality have occurred. In FY 2019, we delivered two conference presentations on this work. The final deliverable associated with this work is an M.S. Thesis (Bransky, 2020) that was successfully defended in May 2020 and an associated journal manuscript and data release that are in review (Bransky and others, *in review* a, b).

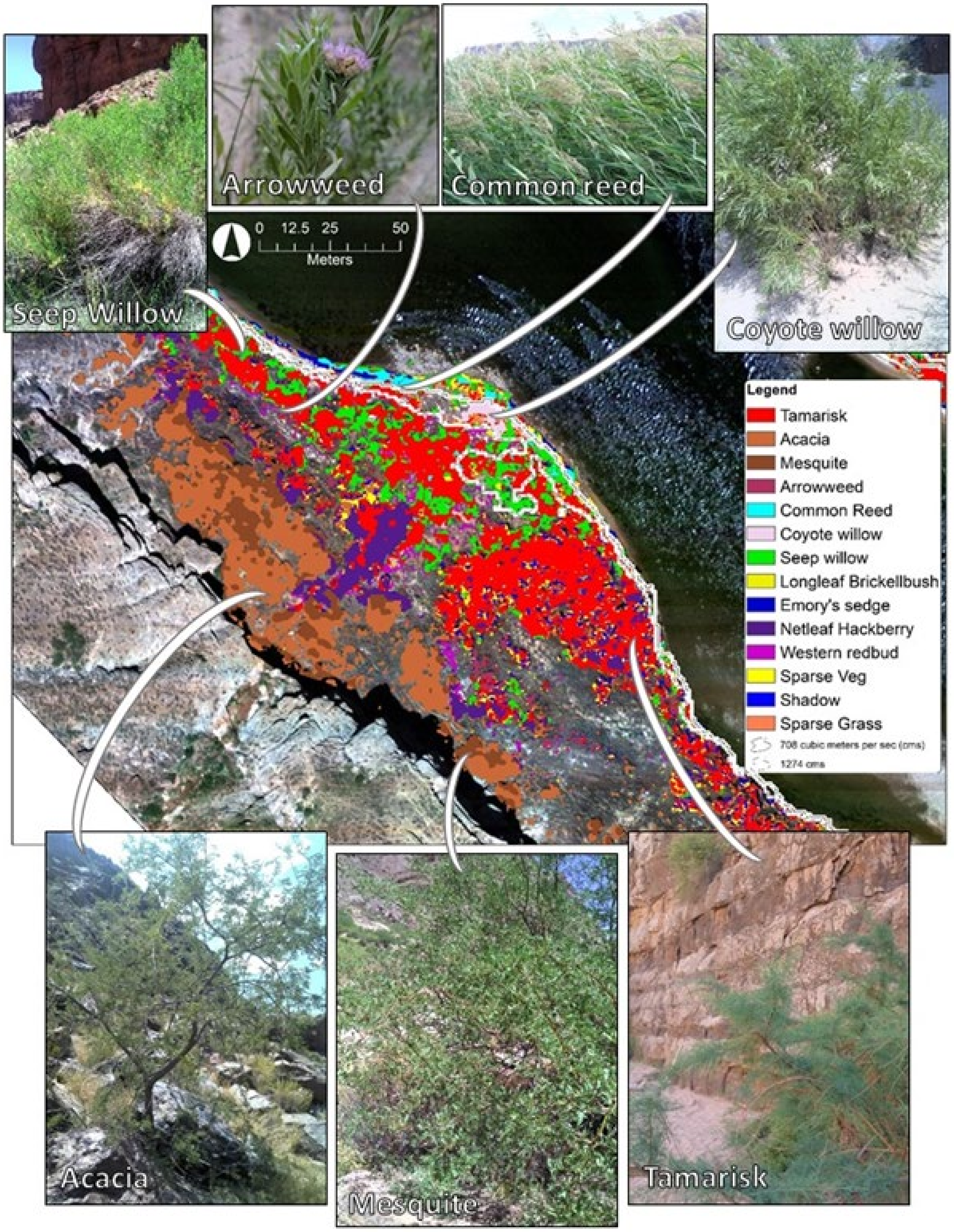

Figure 2. Example map of remote sensing vegetation species classification map of Durning and others (2018), with photos of dominant species. The area displayed is river-right below Saddle Canyon (river kilometers from Lees Ferry, 77.6).

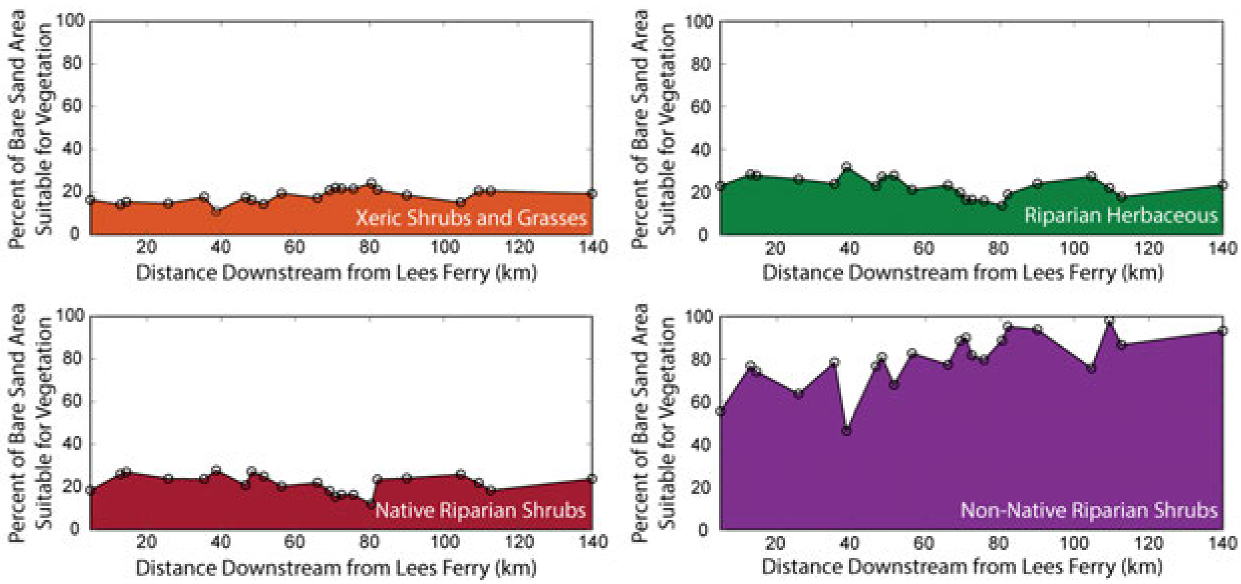

Figure 3. Results of vegetation habitat suitability modeling published by Kasprak and others (2020) showing the percent of contemporary bare sand sutiable for future encroachment by 4 different vegetation types at 22 sandbar sites in Grand Canyon.

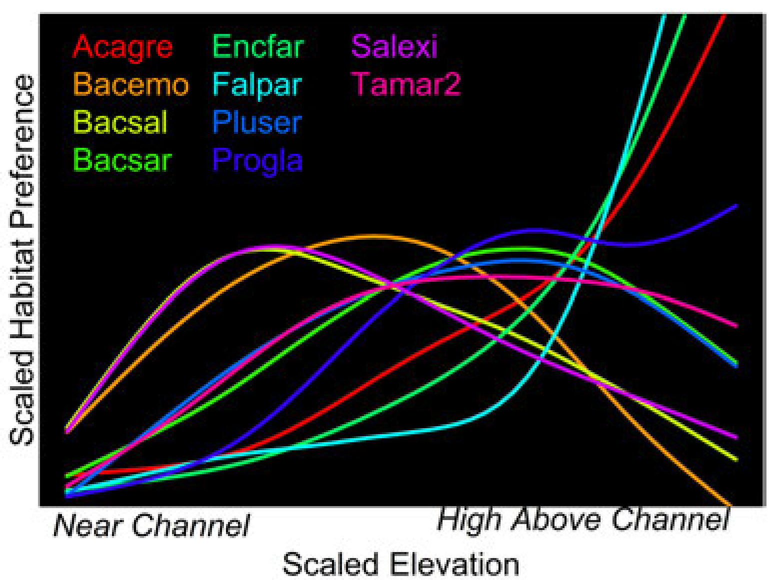

Figure 4. Example of predicted habitat suitability as a function of a local hydrological gradient, elevation above the channel, for the most common woody plant species in the CRe. Species are: Acagre - *Acacia greggii*, Bacemo - *Baccharis emoryi*, Bacsal - *Baccharis salicoides*, Bacsar - *Baccharis sarothroides*, Encfar - *Encelia farinosa*, Falpar - *Fallugia paradoxa*, Plusar - *Pluchea sericea,* Progla - *Prosopis glandulosa*, Salexi - *Salix exigua*, Tamar2 - *Tamarix* spp. Results of vegetation habitat suitability modeling were used by Kasprak and others (2020).

C.3. Vegetation Responses to LTEMP Flow Scenarios

In this Project Element, we synthesize site- and landscape-scale, ground- and remote sensing monitoring data to identify environmental stressors with strong effects on species composition and location and progressively develop better predictive models of how Long-Term Experimental and Management Plan (LTEMP; US DOI, 2016) flows will alter vegetation. During this work plan, these broad topics were approached by examining how climate may be modifying vegetation responses to flows, how vegetation is altering sediment deposition, and extending vegetation habitat prediction beyond the observed hydrological variability of the CRe.

In 2018, we published initial models that identified the interactive effects of climate and flow regime on vegetation composition (Butterfield and others, 2018). This research determined that riparian plants closely tracked hydrological variation and minimum temperature and that species likely to be located in wetter, more flooded conditions, also tend to be found in wetter climatic conditions. In hotter sections of the CRe with lower precipitation, plant species tended to have lower tolerances for inundation duration (less flood tolerant). These results suggest that increasing temperatures and drought may reduce inundation tolerance of riparian vegetation, and/or increasing flooding in the CRe may reduce the resilience of riparian vegetation to heatwaves and drought. These models were further applied to projections of changes in bare sand area throughout the canyon (see Element C.2 above, Figure 3, and Kasprak and others, 2020). More broadly, these types of models generally predict habitat suitability as a function of local hydrological (for example, Figure 4) and climatic variables that can be applied to numerous objectives.

Stemming from the niche modeling results of Butterfield and others (2018), the physiological responses of *Pluchea sericea* (arrowweed) to flooding were experimentally tested in a 2019 pilot study with special consideration of climate provenance (Figure 5). This experiment assessed if *P. sericea* collected from across a temperature range responded differently to flooding. A suite of morphological and physiological traits were measured to characterize plant responses and were evaluated with regard to provenance (collection location), flood depth, and their interaction. Across provenances, *P. sericea* exhibited increased biomass with less flooding. Plants from different climate provenances exhibited significantly different trait ranges when flood depth was accounted for, suggesting some genetic control over these traits. This experiment provides the initial framework for future flow regime experiments, input data for modeling efforts, and can be useful for vegetation management decision support (C.4). Results from this study were presented at the August 2020 Adaptive Management Work Group meeting.

Figure 5. Experiment testing the physiological and morphological responses of arrowweed (*Pluchea sericea*) to a range of flood depths. Conducted in summer of 2019, this experiment provided data on arrowweed flood tolerance and an initial framework for future flow regime studies.

The results of collaborative research regarding the effects of riparian vegetation morphology on fluvial sediment dynamics was published in River Research and Applications in 2020 (Butterfield and others, 2020). This work merged the long-term sandbar monitoring topographic maps (see Project B) with vegetation classifications derived from the 2013 airborne imagery (Durning and others, 2018) to identify associations between plant morphological guilds and changes in elevation, providing estimates of net deposition or erosion over the period from 2013-2018 that are associated with different plant groups. This research determined that plants can significantly modify sand deposition, but that plants with different morphologies (branching architecture, height) impact fluvial processes differently. This analysis also suggested that flow regulation may be selecting for a narrow subset of morphological guilds within the CRe, as only a subset of plant morphologies that are present in free-flowing rivers are present.

To improve predictions of vegetation response in the CRe to a wide range of hydrological and climatic scenarios, we developed a novel workflow that analyzes ecological niches of CRe species across their full distributions across other western river systems (Butterfield and others 2020b). To test this novel integration that uses existing datasets, we conducted an initial study of how willow species' hydrological and climatic niches covary among closely related willow species, including Goodding's willow (*Salix gooddingii*) and coyote willow (*Salix exigua*). Among willow species, riparian dependence increased under warmer and drier climates. As a taxonomic group, willows compensated for increased atmospheric demand through restricting their ecological niches to reliable water supplies rather than developing drought-resistant physiological strategies. These initial analyses provided a proof of concept of this new methodology and will improve our ability to predict species' responses to alternative flow scenarios.

C.4. Vegetation Management Decision Support

GCMRC partnered with National Park Service (NPS) and Native American Tribes on the LTEMP Riparian Vegetation Mitigation Project C.7 Experimental Vegetation Treatment by providing scientific support, providing input on project design and implementation, partnering on monitoring and research efforts, providing objective advice on project efficiency and adaptive management, manage project data, and participating in meetings.

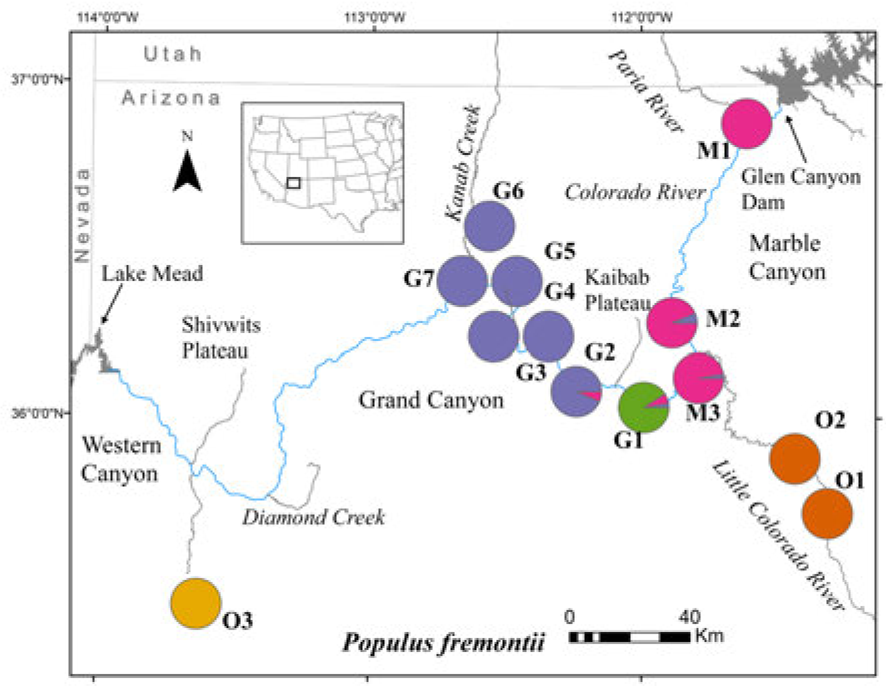

Figure 6. Map illustrating genetic structure of *Populus fremontii* (Fremont cottonwood) based on Discriminant Analysis of Principle Components results. Site labels indicate geographic locations: O = outside of the canyons, M = Marble Canyon, G = Grand Canyon. The color proportions in each pie indicate the membership probability for each group, such that the same color indicates genetically similar sites.

In cooperation with GRCA (Grand Canyon National Park) and GLCA (Glen Canyon National Recreation Area), we assessed the genetic structure and differentiation of Fremont cottonwood (*Populus fremontii*), Goodding's willow (*Salix gooddingii*), coyote willow (*Salix exigua*), and honey mesquite (*Prosopis glandulosa*) in the Grand Canyon region. This work will inform the development of genetically appropriate planting materials for the LTEMP experimental vegetation management treatments. The results of this study indicate that the riparian species only found in tributaries to the Colorado River (cottonwood) exhibits reduced gene flow across the region and more genetic structure than the other species (Figure 6), so will require greater consideration when choosing native plant materials for vegetation management. Genetic patterns in the other three species indicate that plant materials could be collected and planted across the region without altering existing genetic structure.

Pre-treatment vegetation composition and cover data were collected at RM -7.1 (Lunch Beach) in August 2018. This location was selected by GLCA for dead tamarisk removal in late 2018 and subsequent native vegetation reestablishment. Pre- and post-treatment vegetation and topographic survey data were collected at two vegetation removal sites in GRCA, RM 70.1 (Basalt) and RM 122.7 (122 Mile). These vegetation removal sites are coincident with the long-term monitoring sandbar sites (see C.1 and Project B). Two other previously treated areas, RM -6.6 (-6 Mile) and RM 93.8 (Granite Camp), are also long-term monitoring sandbar sites.

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Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$240,738	$850	$2,500	$180,273	$0	$39,078	**$463,439**
Actual Spent	$212,540	$873	$3,111	$361,425	$0	$40,710	**$618,659**
(Over)/Under Budget	**$28,198**	**($23)**	**($611)**	**($181,152)**	**$0**	**($1,632)**	**($155,220)**
FY19 Carryover	**$267,364**					**FY20 Carryover**	**$112,144**

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

- Lower costs in salary was due to a vacancy and one staff member serving on a detail. Work related to the vacancy was accomplished through cooperative agreements.
- Higher costs in cooperative agreements was due to additional funding to conduct work associated with a vacancy at GCMRC and the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

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

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Summary

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

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

The Glen Canyon Dam (GCD) Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS; U.S. Department of Interior, 2016a) predicts that conditions for achieving the goal of preservation for cultural resources, termed "preservation in place," will be

enhanced as a result of implementing the selected alternative. High-Flow Experiments (HFEs) are one component of the selected alternative that will be used to resupply sediment to sandbars in Marble and Grand Canyons, which in conjunction with targeted vegetation removal, is expected to resupply more sediment via wind transport to archaeological sites, depending on site-specific riparian vegetation and geomorphic conditions. However, HFEs have been shown to directly erode terraces that contain archaeological sites in Glen Canyon National Recreation Area (GLCA; East and others, 2016; U.S. Department of Interior, 2016a). HFEs have also been shown by Sankey and others (2018b) to rebuild or maintain sandbars that provide sand to resupply aeolian dunefields containing archaeological sites throughout Marble and Grand Canyons. Aeolian dunefields were resupplied with sand from HFE deposits in half of the flood-site instances monitored after the 2012, 2013, 2014, and 2016 HFEs (Sankey and others, 2018b). They also found evidence for cumulative effects of sediment resupply of dunefields when annual HFEs are conducted consistently in consecutive years (Sankey and others, 2018b).

Goals and Objectives

This project quantifies the geomorphic effects of ongoing and experimental dam operations as well as the geomorphic effects of riparian vegetation expansion and management, focusing on effects of HFEs on the supply of sediment to cultural sites and terraces. The ongoing and experimental dam operations and vegetation management of interest are those that are undertaken under the LTEMP Record of Decision (ROD; U.S. Department of the Interior, 2016b) through 2036.

Science Questions Addressed & Results

The data and analyses from this project will allow the GCDAMP to objectively evaluate whether and how flow and non-flow actions directly affect cultural resources, vegetation, and sediment dynamics. It will also allow determination of how flow and non-flow actions will ultimately affect the long-term preservation of cultural resources and other culturally valued and ecologically-important landscape elements located within the river corridor downstream of GCD.

There are two elements to this project:

- D.1. *Geomorphic Effects of Dam Operations and Vegetation Management*
- D.2. *Cultural Resources Synthesis to Inform Historic Preservation Plan*

Monitoring and other work completed during FY 2018-20 are described below for each Project Element.

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

FY 2018

- A monitoring trip was conducted in May of 2018. Eight archaeological sites were surveyed with lidar per the protocol described in the GCMRC plan for monitoring effects of geomorphic processes at archaeological sites in Grand and Glen Canyon (shared with stakeholders as a draft plan in 2016 during the FY 2015-17 TWP, and again more recently with signatories of the Programmatic Agreement for Cultural Resources as part of the Historic Preservation Plan[1]).
- Weather data were collected at six stations, one at Ferry Swale (river mile (RM) -11) in Glen Canyon, one at Lees Ferry, and one at each of four Marble and Grand Canyon archaeological sites (e.g., Caster and others, 2014, 2018; Sankey and others, 2018a, b). Stations collected measurements of rainfall, wind speed and direction, temperature, barometric pressure, and relative humidity at 4-minute timesteps.
- At three sites, stationary cameras took photographs up to four times per day to record information about the timing and nature of landscape change.
- Monitoring data described above were processed and archived at GCMRC.

FY 2019

- GCMRC Project D staff helped the National Park Service (NPS) design experimental vegetation removal treatments intended to increase the aeolian transport of Colorado River sediment, deposited by HFEs, to archaeological sites. The treatments focused on locations with coupled sandbars and archaeological sites that Grand Canyon NPS Archaeology staff monitor for visitor impacts and that USGS-GCMRC has specifically monitored for changes in geomorphic condition tied to dam-operations using lidar remote sensing and weather stations during the past decade. The treatments were designed to also achieve LTEMP vegetation management elements of: (i) controlling nonnative plant species affected by dam operations, such as tamarisk, and (ii) removing vegetation encroaching on campsites, in addition to (iii) managing vegetation to assist with cultural site protection. NPS staff and tribal youth from the Ancestral Lands Conservation program implemented the proposed vegetation removal treatments at five sites during a field campaign via river trip conducted in April 2019. Dr. Sankey, Project PI, participated in the trip to provide science support for the implementation of the vegetation removal treatments. GCMRC Project D staff subsequently conducted their annual field campaign via river trip (described in the next bullet) immediately following the NPS trip in order to collect initial monitoring data for the vegetation removal treatments.

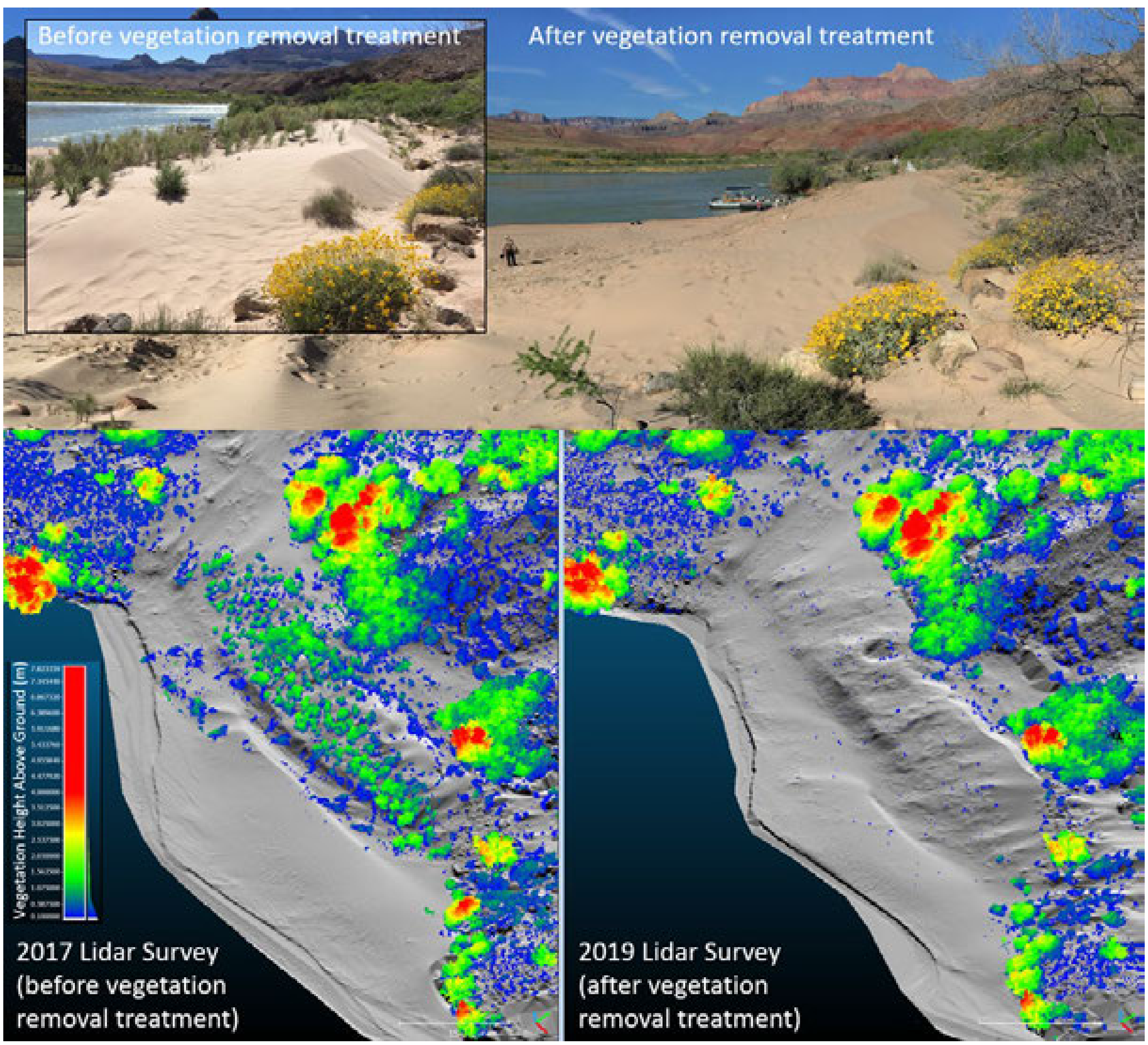
- A field campaign to monitor changes in geomorphic condition tied to dam operations and vegetation management was conducted via river trip in May of 2019. Six archaeological sites were surveyed with lidar. Five of the sites were those at which the NPS had conducted experimental vegetation removal treatments in April 2019.
- Weather data were downloaded from the project's stations (described above for FY 2018) during field campaigns. After over 15 years of operation, the weather stations needed to be updated in 2019 to ensure data continuity. Weather station equipment was repaired and upgraded at existing stations, and a new weather station was installed at Soap Creek (RM 11). A total of six stations collected weather monitoring data during 2019, including a weather station fitted with a satellite link at Lees Ferry.
- Stationary cameras took photographs up to four times per day at three sites.
- All monitoring data acquired in 2019 were processed and archived at GCMRC.
- A USGS Fact Sheet (Cook and others, 2019) was published by Project D staff which summarizes the state of the science that has examined effects of dam operations to archaeological sites in Grand Canyon. The fact sheet focuses on the roles that:
    - Glen Canyon Dam has played in reducing sand resources at archaeological sites, thus decreasing the potential for long-term preservation of the sites in place;
    - HFEs can contribute in increasing sand resources at some archaeological sites in order to improve in-situ preservation potential;
    - Vegetation management currently being implemented by the NPS with GCMRC's assistance might play in increasing sand resources at archaeological sites in order to improve in-situ preservation potential.

FY 2020

- GCMRC Project D staff continued to help the NPS implement experimental vegetation removal treatments intended to increase aeolian transport of Colorado River sediment deposited by HFEs to archaeological sites. Grand Canyon NPS staff implemented the proposed vegetation removal treatments at five sites during a field campaign via river trip conducted in September 2020. Note that the trip, originally scheduled for April 2020, was postponed owing to the COVID-19 pandemic. The treatments focused on removing regrowth of vegetation at locations where vegetation had been previously removed by NPS in 2019 as well as at Soap Creek (RM 11) where a new weather station was installed in May 2019. The work was carried out by NPS staff. Dr. Sankey from USGS-GCMRC participated in the trip to provide science support for the implementation of the treatments.

- A GCMRC Project D field campaign to monitor changes in geomorphic condition tied to vegetation management and dam operations was conducted via river trip in June of 2020. Note that the trip was originally scheduled for May 2020 but was postponed owing to the COVID-19 pandemic. Fifteen archaeological sites were surveyed with lidar. Five of the sites were those at which the NPS had conducted experimental vegetation removal treatments initially in April 2019 and then again in September 2020.
- Weather data were downloaded from the five stations located below Lees Ferry, AZ during the field campaign.
- Stationary cameras took photographs up to four times per day at three sites.
- All monitoring data acquired in 2020 were processed and archived at GCMRC.
- A USGS Open-File Report manuscript summarizing archaeological site monitoring data acquired from 2010 to 2020 has been completed by project staff and is currently in press with the USGS Science Publishing Network (SPN). The report is titled "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." Publication has been delayed from 2020 by the USGS SPN owing to the COVID-19 pandemic, and it is now anticipated that the report will be published in 2021.
    - The report summarizes baseline data collected at 33 archaeological sites and 61 individual archaeological features. The report also summarizes the geomorphic changes that have been documented at sites with two or more lidar monitoring surveys between 2010 and 2020. In the report, geomorphic changes for sites with and without multiple lidar monitoring surveys are presented as visual changes in gullying (Hereford and others, 1993; Leap and others, 2000) and sandbar connectivity by wind (East and others, 2016) by summarizing past and recently updated monitoring classifications. These data provide the framework for a robust monitoring program of over 30 archaeological sites that can be repeated over a three year interval in the future (e.g., each site visited once per Triennial Work Plan) to test the hypotheses presented by East and others (2016) regarding the role of sediment connectivity for in-place preservation of cultural resources.
    - This report and the monitoring data contained therein will provide baseline data (see Figure 1 below) for evaluating the experimental vegetation management treatments which were implemented by NPS per the LTEMP EIS beginning in 2019 and will be continued into the FY 2021-23 Triennial Work Plan.

- Some of these monitoring data also have been used by Sankey and others (2018b) to demonstrate how HFEs can rebuild or maintain sandbars that provide sand to aeolian dunefields containing archaeological sites throughout Marble and Grand Canyons. Aeolian dunefields were resupplied with sand from HFE deposits in half of the instances monitored after the 2012, 2013, 2014, and 2016 HFEs (Sankey and others, 2018b). Sankey and others (2018b) found evidence for cumulative effects of sediment resupply of dunefields when annual HFEs were conducted consistently in consecutive years (Sankey and others, 2018b). Thus, the monitoring data will provide baseline data to evaluate effects of future HFEs in combination with vegetation management for archaeological sites during the FY 2021-2023 Triennial Work Plan.



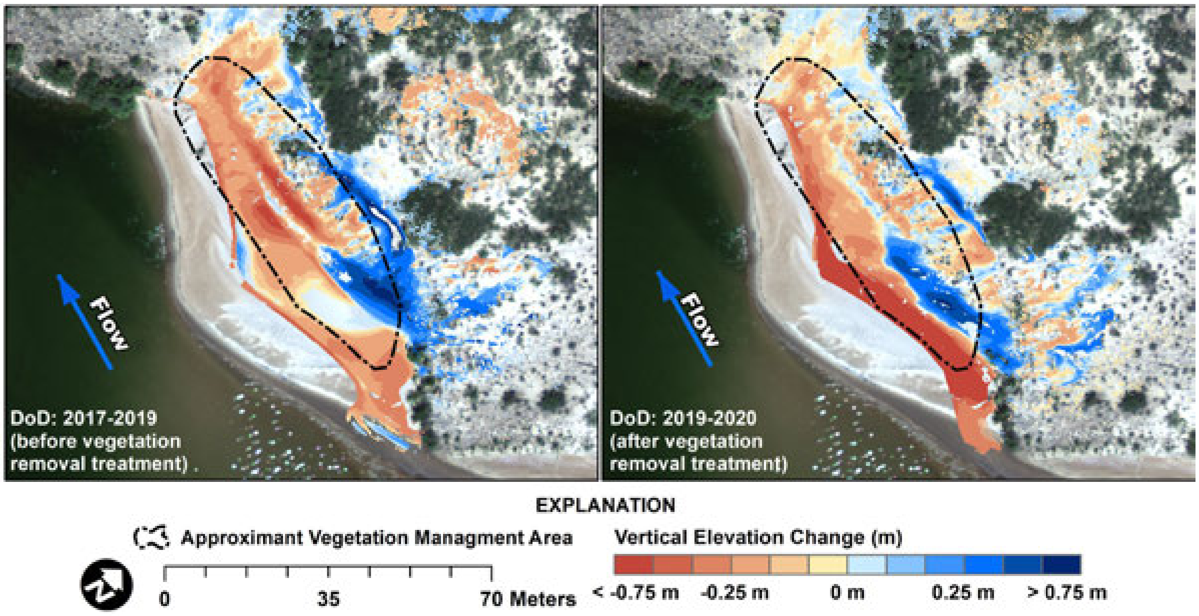


Figure 1. Photos and lidar survey data showing the vegetation removed by the National Park Service during an experimental vegetation management treatment near archaeological site AZ:C13:0321. The treatment at this and other sites is intended to increase sediment storage at the sites by enhancing aeolian transport of Colorado River sand deposited during high-flow experiments from sandbars to archaeological sites. Vegetation removal at this location exposed an aeolian dune that is visible in the photos and lidar data. In the lidar data panels (bottom images, previous page): the grey pixels are the sandy ground surface, and the colored pixels are vegetation; the vegetation pixel colors are scaled by plant canopy height, where cool colors are shorter plants and the warmer colors are taller plants. In the lidar-derived topographic change detection maps (images above), the colored pixels show erosion and deposition of sediment that occurred on the aeolian dune that is derived from and superimposed on the river sandbar at the location.

D.2. Cultural Resources Synthesis to Inform Historic Preservation Plan and Repeat Photography to Inform Project Element D.1.

In the 2018-20 Triennial Work Plan, Project Element D.2 called for preparation of a report summarizing and evaluating past research and monitoring conducted under the 1994 Programmatic Agreement for Cultural Resources, to inform development of a Historic Preservation Plan (Bureau of Reclamation, 2018), as required by the 2017 Programmatic Agreement for the Long-Term Experimental and Management Plan (Bureau of Reclamation, 2017). This was to be followed by a more in-depth exploration of existing monitoring photographs collected by Grand Canyon National Park's cultural monitoring program since 1991. The purposes of the photographic archive evaluation were to determine whether the monitoring photographs were suitable for quantifying physical changes at archaeological sites over time and, if suitable, to analyze and quantify changes. This evaluation of GRCA's cultural monitoring program photographic archives originally had been proposed by the Legacy Monitoring Data Review panel in 2007 (Kintigh and others, 2007).

FY 2018: The synthesis report was completed in September 2018 and served its intended purpose of informing development of the Historic Preservation Plan (HPP), which was completed and adopted by signatories to the new (2017) Programmatic Agreement in November 2018.

FY 2019: In 2019, an evaluation of the NPS photographic collection from the past ~20 years of cultural resource monitoring was initiated. After reviewing hundreds of photographs from a randomly selected sample of archaeological sites, it became apparent that the monitoring photographs — while useful for documenting surficial changes at individual sites — were not well suited for systematically quantifying change. This conclusion was based on several observations and methodological considerations: 1) most of the photographs are low resolution "snap shots" taken with a 35mm analog camera under highly variable lighting conditions and are often of poor quality; 2) the amount of photographic coverage varies widely by site, with some sites having hundreds of photographs while others have only a few; generally, sites with the most coverage are those which receive high levels of visitation from river runners, which makes it challenging to segregate erosion and other damage caused by visitor use from impacts related to dam operations; 3) while many photographs depict the same features over multiple years, the photographic views of these features are taken from a wide variety of angles from year to year, making direct comparisons difficult; 4) changes in the monitoring protocols have resulted in uneven documentation of surface stability and change through time. With regard to factor 4 specifically, after a decade of taking photographs during each monitoring visit regardless of whether or not changes in condition were observed, the NPS archaeology staff changed their monitoring protocols in the late 1990s to only take photographs when a noticeable change was observed. What constituted a change worthy of photographing was not explicitly defined. Furthermore, because sites are monitored at varying and somewhat irregular intervals ranging between once every year to once every five years, it is not possible to determine when a change occurred or whether it occurred during a single moment in time or over a period of several years. All of these factors combined to severely limit the utility of the existing monitoring photography collection for systematically analyzing or quantifying changes in site condition through time.

Since further analysis of the archaeological site monitoring photographs did not appear to be worthwhile, in FY 2019, project D.2 focused mainly on continuing to expand the photographic coverage of changes in riparian vegetation cover and open sand areas throughout the river corridor, with an emphasis on documenting changes associated with specific Project D study sites (both lidar survey sites as well as vegetation removal sites). These photographs document changes in local environmental conditions related to the effects of regulated flows that have affected the current availability and redistribution of sediment in the river corridor.

This work was accomplished through precisely matching existing historical images dating between 1889 through the early 1990s with replicate views of the same locations under current conditions. This work built upon earlier photographic-matching efforts initiated in 2015 during a previous phase of Project D (see Project 4 in the FY 2015-17 TWP as well as Project 12). During FY 2019, a total of 42 matched images were obtained during the May 2019 river trip, bringing the total number of matched historical images collected from the river corridor since 2015 to approximately 200. As in the past, collection of the photo-matches and accompanying vegetation data was accomplished with the aid of two unpaid volunteers.

FY 2020: In FY 2020, we planned to continue the photo-matching effort with the assistance of two unpaid volunteers. Due to the COVID-19 pandemic, the FY 2020 river trip was delayed six weeks, and this also precluded one volunteer – the principal photographer for this project – from participating in field work during June 2020. In the absence of a photographer during the FY 2020 field campaign, we concentrated on revisiting previously matched sites and upgrading the vegetation information that had been collected in May 2016 and May 2017. In addition, we inventoried plant species growing on open beach and dune areas to compare with the plant communities growing in more densely vegetated areas and rockier terrain along the river margins. We revisited 39 previously photographed sites and also photographed and documented two previously unmatched sites, one at the mouth of Monument Creek, river mile 93.9 (Figure 2) and the other at the mouth of Blacktail Canyon, river mile 120.7. Both were originally photographed in 1973 as part of the NPS Colorado River Research Program's recreational capacity (campsite inventory) study (Weeden and others, 1975).

Figure 2. Borden-Weeden photograph taken in July 1973 at the mouth of Monument Creek, river mile 93.9 (upper photograph), matched with the same view in June 2020. Note the somewhat less active, more vegetated condition of the dunes in the 2020 view compared to 1973. Also note how the bunch grasses (primarily *Achnatherum, hymenoides*, aka Indian Rice Grass), which predominated in 1973, have been largely replaced by shrubs (predominantly *Isocoma acradenia*) in the 2020 view, along with the dense thicket of tamarisk trees growing along the river margin in 2020, compared to the open shoreline in 1973.

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Budget

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$207,609	$4,750	$7,100	$0	$0	$30,272	**$249,731**
Actual Spent	$218,498	$601	$3,041	$0	$0	$30,642	**$252,782**
(Over)/Under Budget	**($10,889)**	**$4,149**	**$4,059**	**$0**	**$0**	**($370)**	**($3,051)**
FY19 Carryover	**$18,141**					**FY20 Carryover**	**$15,090**

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

- Higher costs for salary was due to unanticipated effort maintaining instrumentation in support of this and other projects that require remote access to sensors near Lees Ferry.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.

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

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Summary

Temperature and nutrient dynamics can influence both community composition and metabolic rates across many different types of ecosystems (Allen and others, 2005; Brown and others, 2004; Elser and others, 2003; Elser and others, 1996; Yvon-Durocher and others, 2012). Within the aquatic portion of the Colorado River Ecosystem (CRe), there is increasing evidence for the important role of temperature and nutrients as ecosystem drivers. Understanding this role can point to new management actions as well as providing important context for interpreting the efficacy of other management actions. For example, ecosystem responses attributed to the flow regime may, in fact, be partially or fully explained by temperature and/or nutrients. The primary goals of this project are to: 1) identify processes that drive spatial and temporal variation in nutrients and temperature within the CRe, and 2) establish quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels. Parallel work in Lake Powell that aims to identify the controls on nutrient concentrations in the Glen Canyon Dam outflow is ongoing with funding from the Bureau of Reclamation (see Appendix 1).

Goals and Objectives

During the Fiscal Years (FY) 2018-20 Triennial Work Plan, we modified a heat-exchange model previously described by Wright and others (2009) to predict monthly water temperatures throughout the CRe and also collaborated with scientists at Utah State University to develop a more mechanistic, but computationally intensive, model for predicting water temperatures at finer time scales. Improvements in the monthly model include fitting an exponential (rather than linear) curve to water temperatures in Grand Canyon and adding solar radiation as a primary driver of the heat budget. The improved monthly model will allow for a more accurate characterization of thermal conditions present now and in the future that will shape the distribution and abundance of native and nonnative fishes throughout Grand Canyon. To facilitate use of this model by stakeholders, we developed a user-friendly spreadsheet model for distribution once the manuscript and the associated model have undergone peer-review.

Work conducted during the FY 2018-20 Triennial Work Plan also provides further evidence that phosphorus (P) exerts a bottom-up control on food webs in Glen and Marble Canyons (Yackulic, 2020; Korman and others, 2020). A strong positive relationship between biologically available P (soluble reactive phosphorus, SRP) and the density of aquatic insect drift is likely to contribute to fish growth in Glen Canyon (Korman and others, 2020). Dam SRP outflow also appears related to native fish condition as far down as the Little Colorado River (Yackulic, 2020). While the dam is an important source of phosphorus to these upper reaches of the Colorado River, the role of tributary phosphorus inputs is not well characterized. Storms can be responsible for large fractions of total riverine phosphorus loads, and phosphorus-discharge hysteresis can vary substantially (Bowes and others, 2005). During the FY 2018-20 work plan, we established two new auto-samplers on the Paria and Little Colorado Rivers. Due to weak monsoons in both 2019 and 2020, we have only characterized phosphorus concentrations during two Paria River storms and have not yet collected any storm nutrient data from the Little Colorado River. We also conducted pilot work to build a P budget for the Colorado River which included sampling to better characterize the fractional contribution of different forms of P to the overall nutrient pool.

In general, mainstem P concentrations are very low, with the biologically available fraction (SRP) often undetectable (<0.001 mg/L) throughout the river. In fact, we found more variation in SRP during 24-hour sampling at both Lees Ferry and Diamond Creek (undetectable to 0.004 mg/L) than during longitudinal sampling in the Colorado River. While baseflow P concentrations in many tributaries to the Grand Canyon are not high enough to significantly affect mainstem nutrient budgets, preliminary sampling in 2018 and 2019 suggests that storm-based P inputs from the Paria River may contribute significantly to the CRe P budget. Still, the degree of storm-to-storm variability appears quite high, with peak storm total P concentrations ranging between 5 and 30 mg L^{-1} in the two storms sampled thus far (August 2018 and November 2019). Sampling conducted in July 2020 aims to parse the forms of P in different tributaries and to develop a protocol for citizen science-based P sampling (to target monsoon storms) during the next work plan.

In addition, watershed disturbances such as wildfires have been linked to increased stream P availability in other ecosystems (Emelko and others, 2016), but the potential for tributary fires to affect the CRe is not known. During this work plan we analyzed archived aquatic insect samples collected in light traps near Shinumo Creek both before and after a fire-storm sequence in the Shinumo watershed (Galahad Fire). This was done to better quantify the potential role of wildfire on food web phosphorus availability.

We found significantly higher total phosphorus (TP) content of Diptera collected after the Galahad Fire and storm than from those collected before (two-sided t-test $p<0.05$), with emergent Diptera containing an average of 20% more P after the fire than before (Ryan and others, 2020). This suggests a potentially important role for wildfire in mobilizing nutrients.

During the FY 2018-20 Triennial Work Plan, we also investigated how mainstem nutrient availability might change with dam management. Specifically, we examined the effects of both the flows associated with the Bug Flows experiment in 2018 and 2019 and the November 2018 fall HFE on nutrient concentrations in Glen Canyon. Higher concentrations of SRP at depth in Lake Powell during the November 2018 HFE led to an increase of ~ .001 mg/L SRP in dam outflow during the HFE. Bug Flow nutrient concentrations were measured in Glen Canyon during both 2018 and 2019. We report no significant differences in SRP or TP between weekend and weekday water. We did observe significantly higher nitrate concentration (by about .04 mg/L NO3-N) during weekdays than on the weekend (two-sided t-test, $p=0.01$) during August 2019 sampling ($n=14$), but this variation is relatively small compared to the background nitrate concentration during the sampling (0.31 mg/L).

Under the FY 2018-20 Triennial Work Plan, we made progress in developing and applying models of gross primary production (gpp) to understand river-wide patterns in gpp and link the base of the food web to drivers including light and nutrients. This included the deployment and maintenance of 10 MiniDOT oxygen sensors throughout the river from April-September 2018 and 2019 and July-September 2020. These loggers, in addition to the longer term YSI loggers, provide integrated estimates of gpp across most of the Colorado River through Grand Canyon (Figure 1). We used longer term YSI data to look at the effect of high flow events, showing reduced gpp after high flow events relative to years with no high flow event. We also developed a modified model to estimate gpp in Glen Canyon that requires significantly less processing time than previous models. In FY 2020, we focused on patterns in gpp related to the bug flows, implementing a new light process error model for gpp. Adjusted weekend water releases due to bug flows had measurable effects on riverine gpp, with 9 of 12 reaches in Marble and Grand Canyon yielding higher gpp during weekends than during the week.

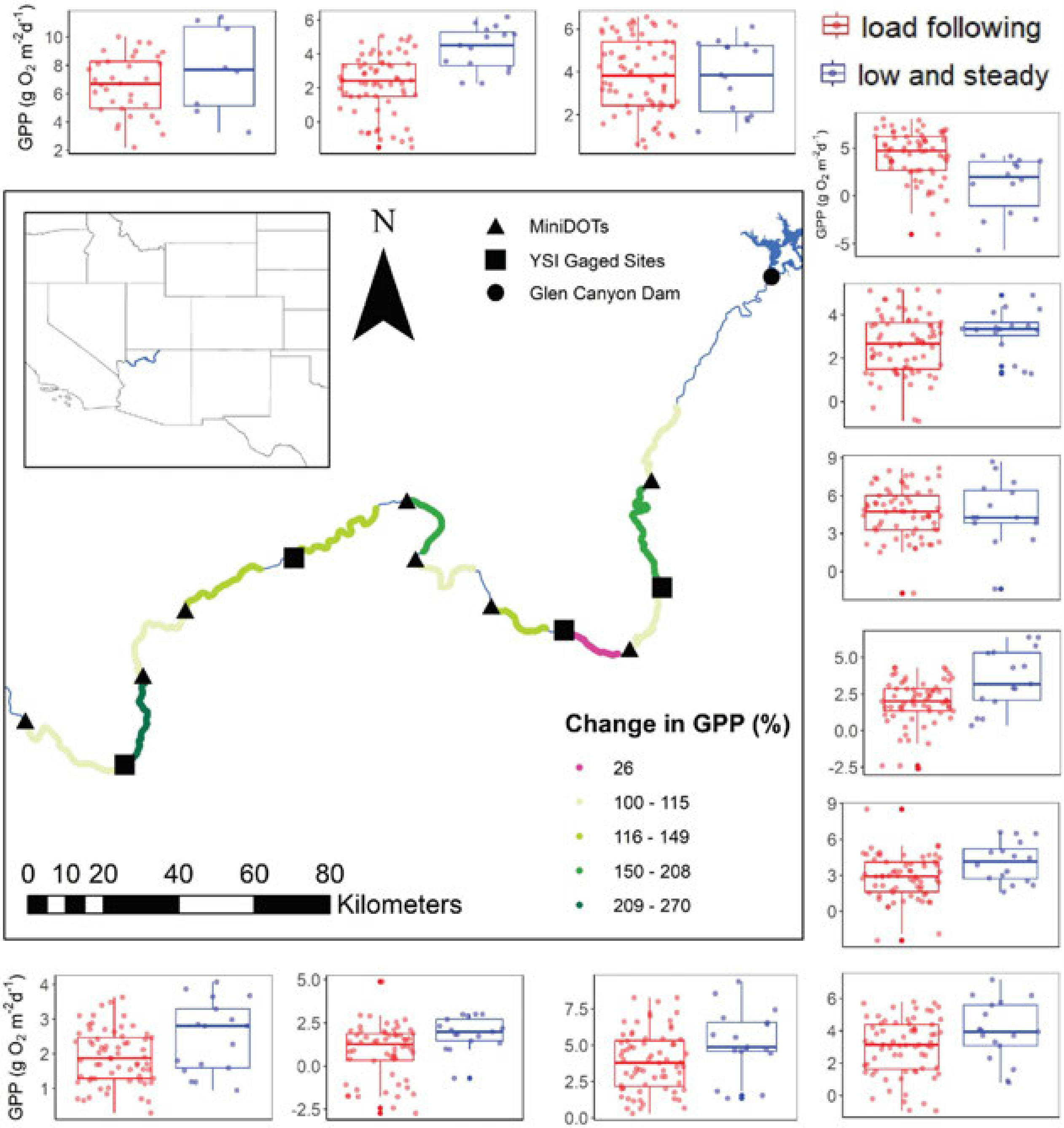

Figure 1. Relative increase (green) or decrease (pink) of gross primary production (gpp) rates from hydropeaking to low and steady flows in 12 reaches on the Colorado River in May and June of the 2018 and 2019 Bug Flow experiment. The length of each modeled reach is estimated based on gas transfer (80% turnover reach). The experiment maintained normal load following flow during the weekdays and adjusted to low and steady flows during the weekends. 9 of 12 reaches experienced elevated gpp on the weekend low and steady flow, relative to the weekday load following flow. For box whisker plots, sites are positioned in clockwise order with the most upstream reach in the upper left and the most downstream reach on the lower left; boxes demarcate the 25th and 75th percentiles; the horizontal lines indicate median concentrations; the whiskers extend to the largest value less than 1.5 times the interquartile range. Inset map shows the location of the Colorado River reaches modeled here within the southwestern United States. Preliminary data, do not cite (Deemer and others, *in prep).*

In the FY 2018-20 Triennial Work Plan we proposed to construct artificial stream experiments adjacent to the Colorado River to study how multiple trophic levels may respond to elevated temperatures. However, in 2018 the installation of artificial streams at the National Park Service water treatment facility in Lees Ferry failed due to an inability to control water temperature, challenging our ability to test hypotheses on how changes in water temperature and nutrient availability may affect primary production and aquatic biota in response to changes in Lake Powell elevation. Since placing the streams on the banks of the river or at the base of the dam was not permitted, we moved the artificial streams to a more controlled environment at the Rocky Mountain Research Laboratory in Flagstaff. From June-November 2019 we developed laboratory-based artificial streams using Colorado River water, substrate, algae, and New Zealand mudsnails (*Potamopyrgus antipodarum*, hereafter “mudsnails”) to determine the effect of 10 °C, 15 °C, and 20 °C treatments on gpp, diatom and soft algal community composition, and mudsnail growth. Side experiments included investigating the effect of mudsnail grazing on gpp under the three temperature treatments and investigating whether native fishes (*Gila cypha* [humpback chub], *Gila robusta* [roundtail chub], *Catostomus latipinnis* [flannelmouth sucker]) consume mudsnails. We finished these experiments in FY 2020 and will soon begin analyzing the data.

We continued the development of a semi-automated technique for classifying submersed aquatic vegetation from underwater imagery, providing a means for future monitoring of aquatic vegetation change in Glen Canyon. In 2018, we began the process of developing machine learning tools to classify species using imagery collected in August 2016. In 2019, we established two permanent reaches with transects in Glen Canyon and took approximately 30,000 underwater images that will provide baseline information to assess future aquatic vegetation change over time. In 2020, we switched to a more user-friendly and faster image processing platform and continued analysis of images taken in 2019. We will continue this work in the FY 2021 work plan using existing images from the 2016 and 2019 trips.

While more progress was made in conceptually developing an ecosystem model in FY 2019 than in FY 2018, systematic underfunding across modeling projects combined with several unplanned activities requested by stakeholders and managers, severely hampered progress in turning this conceptual model into a statistical model. Progress will continue to be slow so long as modeling projects remain underfunded.

Science Questions Addressed & Results

E.1. Temperature and Nutrients in the CRe – Patterns, Drivers, and Improved Predictions

Objectives:

- E.1.1. *Improve models for predicting CRe water temperatures*
- E.1.2. *Describe spatial and temporal patterns in riverine nutrient availability between Glen Canyon Dam and Diamond Creek (including an assessment of the relative importance of tributary nutrient inputs to river nutrient budgets), as well as potential processes driving these patterns.*

Sub-element E.1.1.

Water temperature in the Colorado River in Grand Canyon is an important factor that influences the growth, reproduction, distribution, and abundance of native species including the endangered humpback chub. Predicting the response of humpback chub populations to Glen Canyon Dam management alternatives was a high priority in the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS; US DOI, 2016). Monthly water temperature predictions were generated using a linear warming model, but this model overestimates Colorado River temperatures by up to ~2 °C in western Grand Canyon (e.g., Figure 2). To provide better predictions, we modified the current linear model of water temperature (Wright and others, 2009) by changing the functional form to a saturating function and incorporating the effects of solar radiation (in addition to factors such as discharge, air temperature, and release temperature already present in previous model) and major tributary inputs.

The modified heat-exchange model improved temperature predictions by decreasing residual error, with the largest prediction improvements in western Grand Canyon at the Diamond Creek gage (river mile 224, USGS 09404200) and Spencer creek gage (river mile 244, USGS 09404220; e.g, Figure 2). Residuals (i.e., difference between model and observations) were used to analyze model fit and ranged from 0.2-0.3 °C across all months of the year. Mean signed error (i.e., bias) was -0.03 °C, indicating only a small bias in model results when averaged across all months of the year. While this new model allows for more accurate predictions from Glen Canyon Dam to Pearce Ferry, it also allows us to explore how changes in future conditions (i.e., increasing air temperature, decreasing discharge, and warming Lake Powell release temperatures) may change water temperatures throughout the Grand Canyon.

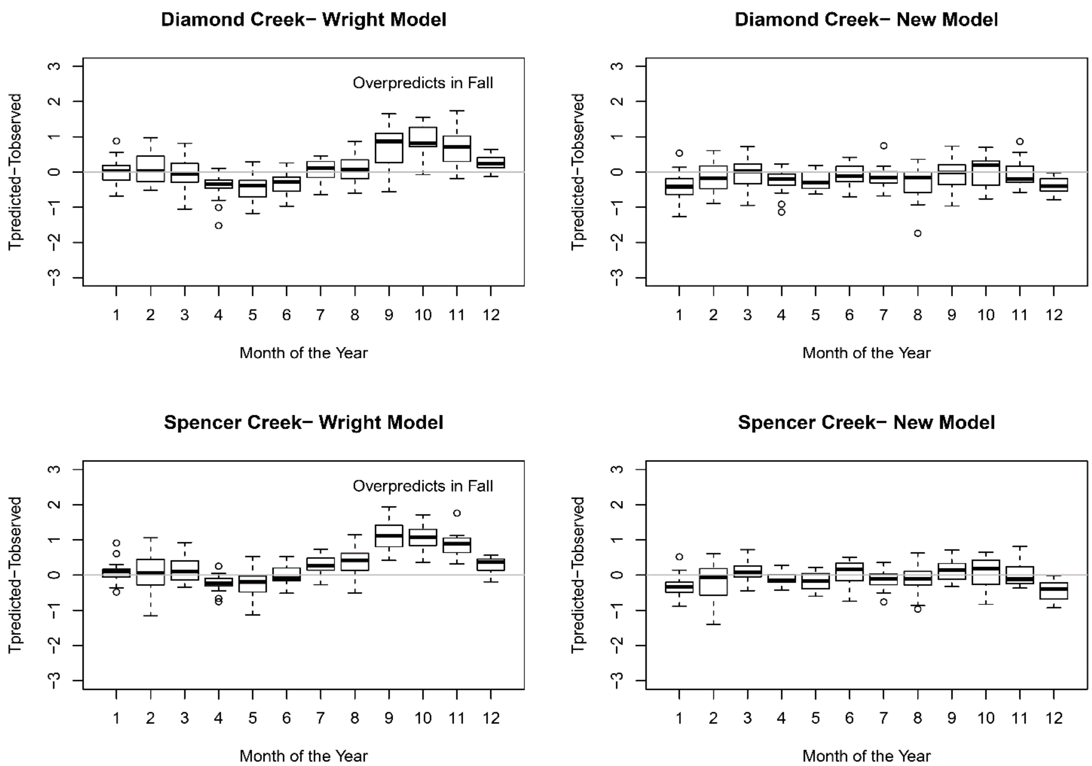

Figure 2. Comparison of residuals from the current model used for modeling water temperature in Grand Canyon (linear; Wright and others, 2009) relative to the new model we developed that includes an exponential decay in warming combined with the use of other data sources including solar radiation. The plot shows the residuals (predicted temperature (Tpredicted) minus observed temperature (Tobserved)) for the last two water temperature stations in Grand Canyon where linear model errors increase, Diamond Creek (river mile 224) and Spencer Creek (river mile 244).

The new monthly water temperature model is also more easily applied in other river systems, and we secured supplemental funding from outside the GCDAMP to analyze water temperature and discharge data already collected as part of the tailwater synthesis project for other portions of the Colorado River Basin (FY 2013-14 work plan, Project Element H.4; FY 2015-17 work plan, Project Element 9.8). These basin-wide water temperature predictions can inform predictions of current and potential future distribution of native, recovering fish populations relative to the risk of potential future invaders into Grand Canyon (e.g., smallmouth bass) from upstream and downstream sources (Figure 3).

Our results indicate that in the future, the thermal regime in most of Grand Canyon will be less affected by increasing air temperatures and declining river flows, and more affected by the elevation (and hence release temperatures) of Lake Powell. Warmer release temperatures will improve thermal suitability for native fish like humpback chub, but also create ideal conditions for nonnative fishes like smallmouth bass which are found in Lake Powell, and occasionally pass through the dam, and are partially responsible for declines in native fish in the upper portions of the Colorado River Basin (Figure 3).

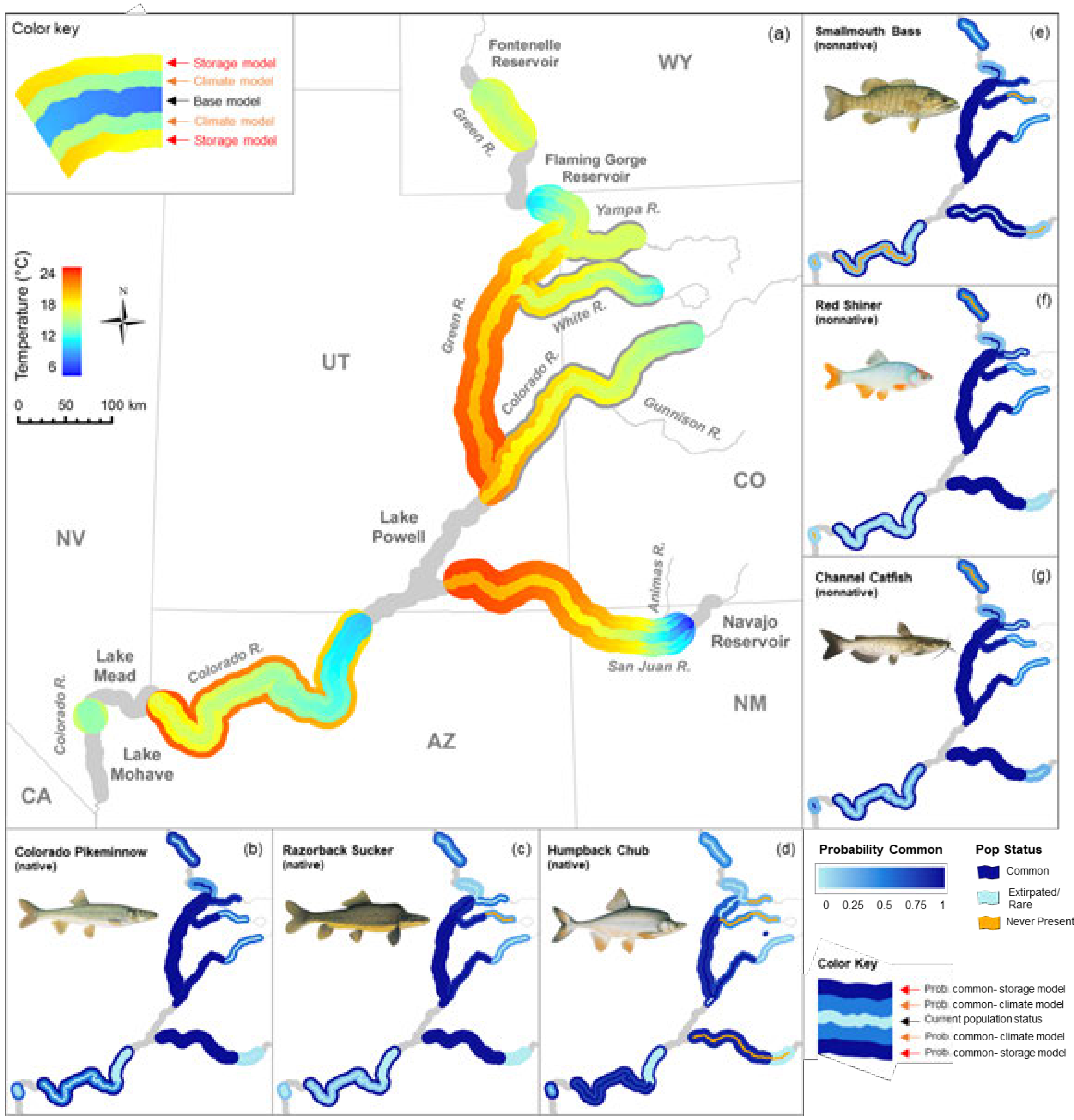

Figure 3. Water temperatures were predicted using parameters developed specific to each river segment using data collected in the FY 2013-14 and FY 2015-17 work plans, current funding from the FY 2018-20 work plan, and supplemental funding from the USGS. (a) Predicted river temperatures in the warmest months for the base (interior), climate (middle), and storage models (exterior). Probability (b) Colorado pikeminnow (*Ptychocheilus lucius*), (c) razorback sucker (*Xyrauchen texanus*), (d) humpback chub (*Gila cypha*), (e) smallmouth bass (*Micropterus dolomieu*), (f) red shiner (*Cyprinella lutrensis)*, and (g) channel catfish (*Ictalurus punctatus*) will become common in the future based on predicted thermal suitability. Interior color represents current species status, middle and exterior colors indicate probability the species will become common in the future based on predicted temperatures from the climate and storage models, respectively. Illustrations: Joseph Tomelleri. Results and model in Dibble and others, *in press*, Ecological Applications.

Sub-element E.1.2.

The purpose of this project is to characterize spatial and temporal patterns in Colorado River nutrient availability downstream from Glen Canyon Dam as well as to explore several processes that can influence the rate at which bioavailable nutrients are cycled and re-supplied to food webs. In FY 2020 we focused on the role of storm-based inputs of phosphorus from the Paria River, the Little Colorado River and smaller tributaries, as well as the potential for using historic suspended sediment data to model P concentrations. We conducted a survey of tributary phosphorus concentrations (July 2020) that developed upon the spring 2017 survey to parse TP into its component forms (both organic and inorganic). Specifically, we measured coarse particulate, fine particulate, organic, calcite-bound, and dissolved fractions of phosphorus at each site (analysis ongoing). At two long term sites (Colorado River near Bright Angel and near Diamond Creek), historical data analysis shows that total phosphorus is strongly correlated with silt and clay concentrations (Figure 4). In future work, we plan to use more continuous estimates of silt and clay concentration to constrain P outflow (a key component to riverwide P budget).

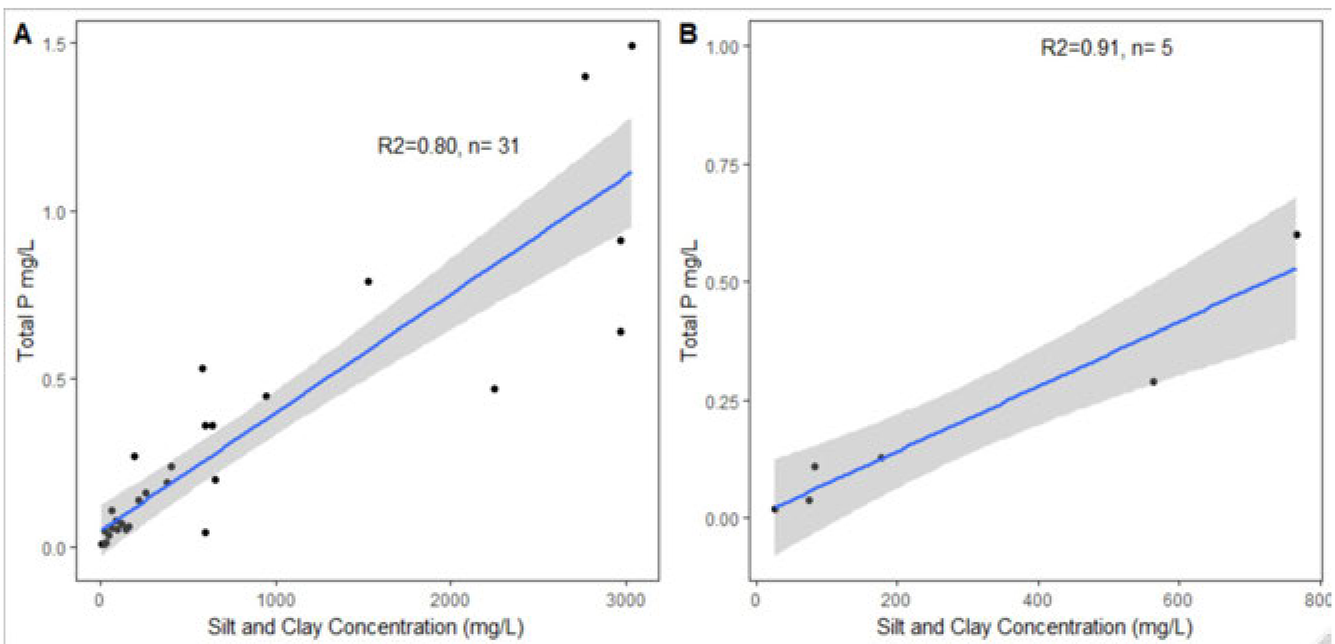

Figure 4. Physical silt and clay measurements predict total phosphorus (TP) concentrations at two long term gage sites on the Colorado River: the Colorado River upstream of Diamond Creek (panel A, gage 09404200) and the Colorado River near Phantom Ranch (panel B, gage 09402500). Measurements at the Colorado River upstream of Diamond Creek (river mile 224) were taken between 1989 and 2019. Less data is available at the Colorado River near Phantom Ranch (river mile 89) and ranges from 2014-2019. Preliminary data, subject to revision.

During FY 2020 we also published a data set describing P, nitrogen, carbon concentrations and stable isotope signatures of aquatic insect light trap samples collected on the Colorado River before and after a major fire in the Shinumo watershed (Ryan and others, 2020). In addition to the elevated post-fire Diptera TP content that we reported in FY 2019, we also report less depleted $\delta^{13}C$ signatures in late season (September) Diptera samples, suggesting less reliance on algae-derived carbon and more reliance on detritus later during the monsoons.

In addition to constraining the important sources of P, a critical question is, how bioavailable is this total phosphorus coming from the Paria River (since very little of it is dissolved). While SRP is considered the most bioavailable form of P, bacteria and plants can also access other P fractions with varying levels of difficulty. Thus, it is important to characterize the quality (e.g., bioavailability) of P entering the river and not just its total concentration. In FY 2019 we ordered equipment and made plans to conduct a series of bioassays to better discern the role of pH and temperature on P cycling at the sediment water interface. These bioassays will assess total protein and alkaline phosphatase (methods we developed in FY 2018) together with major water column P forms. The last-minute loss of a student intern in FY 2019 and complications related to COVID-19 resulted in the project's postponement until the FY 2021-23 work plan.

E.2. Linking Temperature and Nutrients to Metabolism and Higher Trophic Levels

Objectives:

- E.2.1. *Determine drivers of ecosystem metabolism (including primary production and respiration) throughout the CRe*
- E.2.2. *Document aquatic vegetation composition at fixed sites in Glen Canyon and develop a monitoring scheme to track future changes*
- E.2.3. *Use artificial stream experiments to study how multiple trophic levels may respond to elevated temperatures*
- E.2.4. *Develop ecosystem models linking temperature and nutrients to higher trophic levels.*

Sub-element E.2.1.

The purpose of this project is to link information about patterns in riverine nutrients and temperature to the base of the food web, primary production. Primary production in rivers can be estimated from diel patterns of dissolved oxygen. Long-term dissolved oxygen data are available at six sites throughout the Grand Canyon and can be analyzed to yield time-series of primary production. In FY 2018 we compared seasonal patterns of gpp at these long-term sites and found a lack of synchrony between sites.

To follow up on these findings, a network of 10 additional oxygen sensors (PME MiniDOTs equipped with wipers) were deployed throughout the river from April-September 2018 and 2019 and July-September 2020. Preliminary analysis of 2018 and 2019 data show a similar lack of seasonal synchrony.

During this work plan, we have also made progress in developing a two station gpp model for the Glen Canyon reach. In Glen Canyon, the combination of oxygen disequilibrium and load following flows make traditional gpp modeling approaches ineffective and have thus far required time-intensive modeling techniques to provide accurate estimates of metabolism (Payn and others, 2017). Initial gpp estimates in Glen Canyon show an early peak in gpp across most years, but with significant year to year variation (Figure 5).

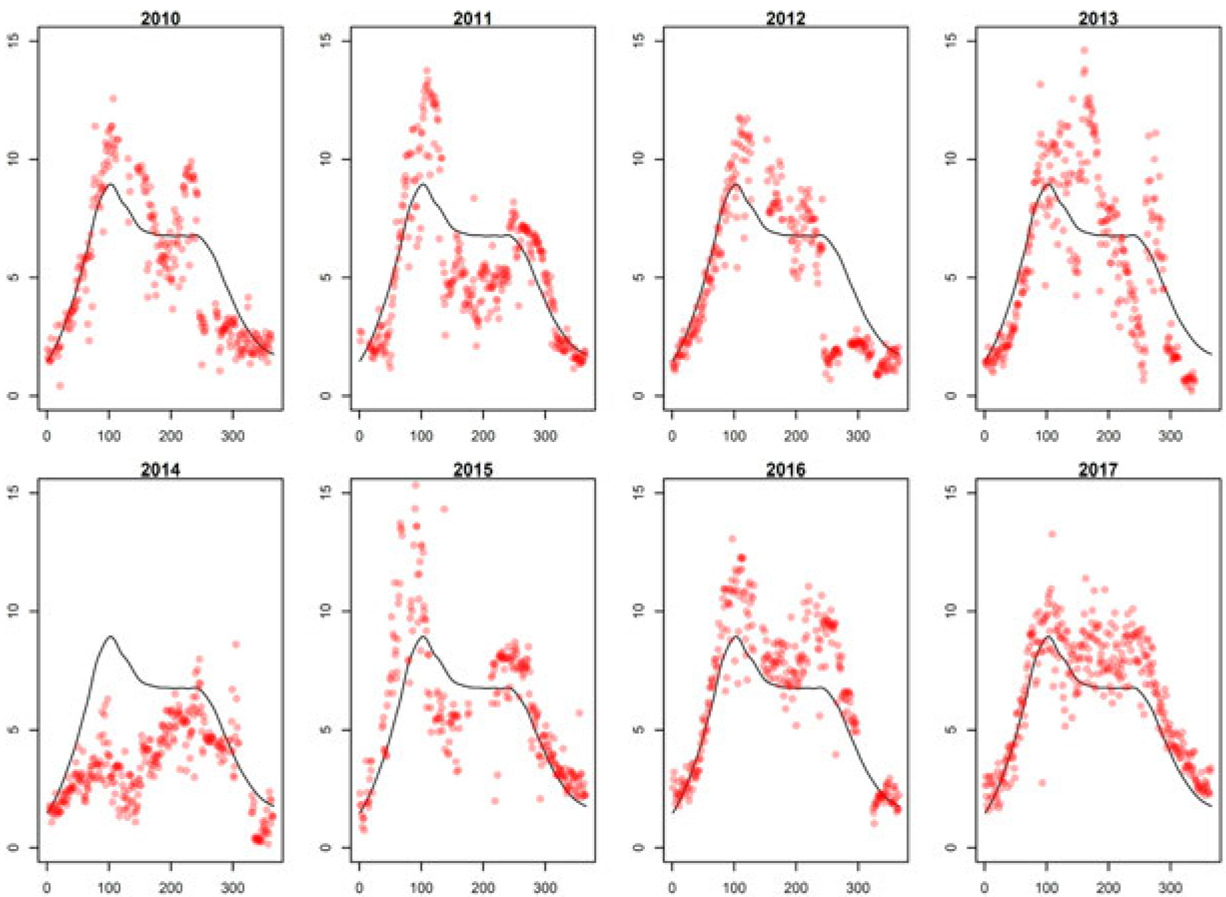

Figure 5. Temporal patterns in gross primary production (gpp) in Glen Canyon (mg O_2 m^{-2} d^{-1}) from 2010-2017. Modeled estimates are from the lower half of Glen Canyon (-8 Mile to Lees Ferry). Red dots indicate daily estimates, the black line shows the eight-year average.

In addition, our analyses have shown that dam management affects downstream gpp. In FY 2020 we focused on the effects of the Bug Flow experiment and report measurable increases in gpp during low and steady weekend water as compared to weekday load following flows. A series of 12 oxygen loggers distributed from RM 36 downstream to RM 250 show measurable increases in weekend gpp in 9 of the 12 reaches. River wide, this effect equates to gpp on the weekends that is approximately 120% of the weekday flows (Figure 1). This pattern is due mostly to the reductions in turbidity that occur during low and steady flows.

Understanding the environmental drivers of primary production at sites where there is bottom-up control of primary production on the food web can provide important management-relevant information. In FY 2018 we employed a similar semi-mechanistic model at Diamond Creek (Hall and others, 2015) to examine the environmental controls on primary production at RM 60. In addition to the drivers considered at Diamond Creek, we added SRP concentrations being exported from Glen Canyon Dam. We found that SRP is nearly as strong a lever on primary production as is the seasonal variation in light (Figure 6). Future work will employ this semi-mechanistic modeling approach at other sites along the river to better discern whole-ecosystem drivers.

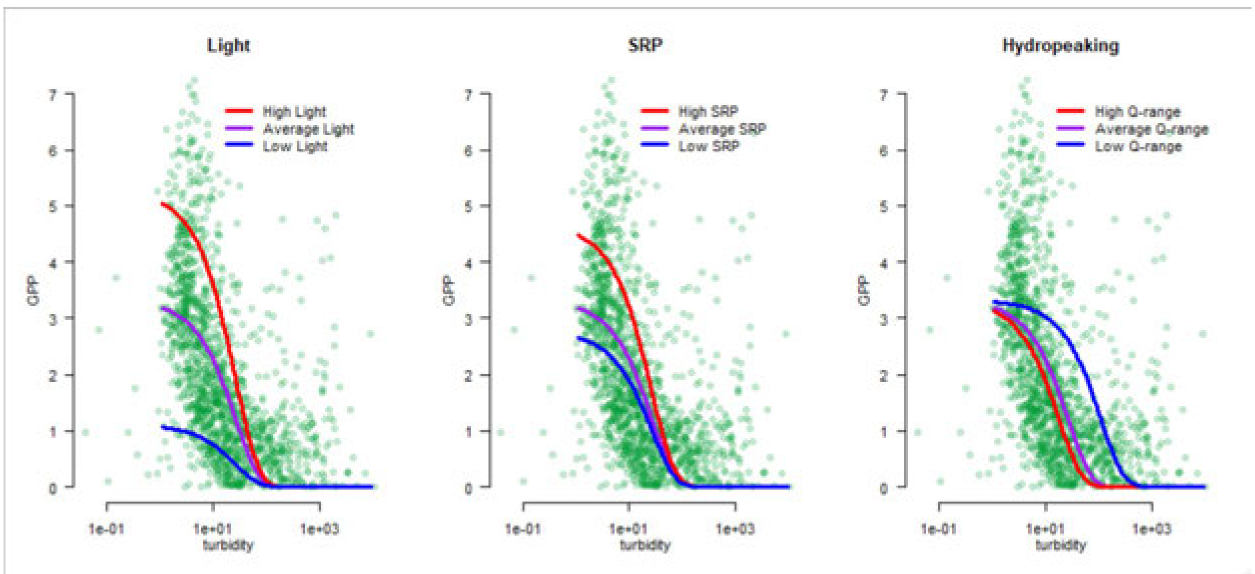

Figure 6. Rates of gross primary production (gpp) across a range of turbidity values in the river reach upstream of the Colorado River above Little Colorado River gage (09383100). The lines represent the relationship between turbidity and gpp across high, average, and low light conditions (left), soluble reactive phosphorus (SRP) concentrations released from Glen Canyon Dam (middle), and sub-diel fluctuations in discharge (right). The red line shows average gpp response to a high light, SRP, or hydropeaking regime, whereas purple lines show response to medium scenarios and blue shows response to low scenarios. SRP at the outflow of Glen Canyon Dam is a similarly strong lever on gpp as is light availability ~120 km downstream. Gpp is in units of g O_2 m^{-2} d^{-1} and turbidity is in Nephelometric Turbidity Units. Preliminary data, subject to revision.

Sub-element E.2.2.

The purpose of this project is to develop a semi-automated aquatic vegetation classification system using underwater imagery combined with the use of machine learning and deep convolutional neural networks to detect annual to decadal scale changes in vegetation cover and species composition in the Colorado River downstream from Glen Canyon Dam. This project will facilitate detection of change to the aquatic vegetation community in response to changes in flow regimes, including experimental flows, as well as changes in ecosystem drivers (nutrients, temperature) in response to changes in Lake Powell elevation.

In FY 2018, we completed the first step of this project by developing a program in Python (v. 3.6.5; Python Core Team, 2018) to classify vegetation species composition and cover using a series of underwater images collected in August 2016. We assessed the ability of two independent biologists to correctly classify plant species within a series of mid- to high-quality underwater images. The two sets of images show a relatively high level of agreement on vegetation type, with precision scores ~0.7-0.8. Image classes from this process were used to train a model to classify the type and cover of other vegetation species within each image (Figure 7).

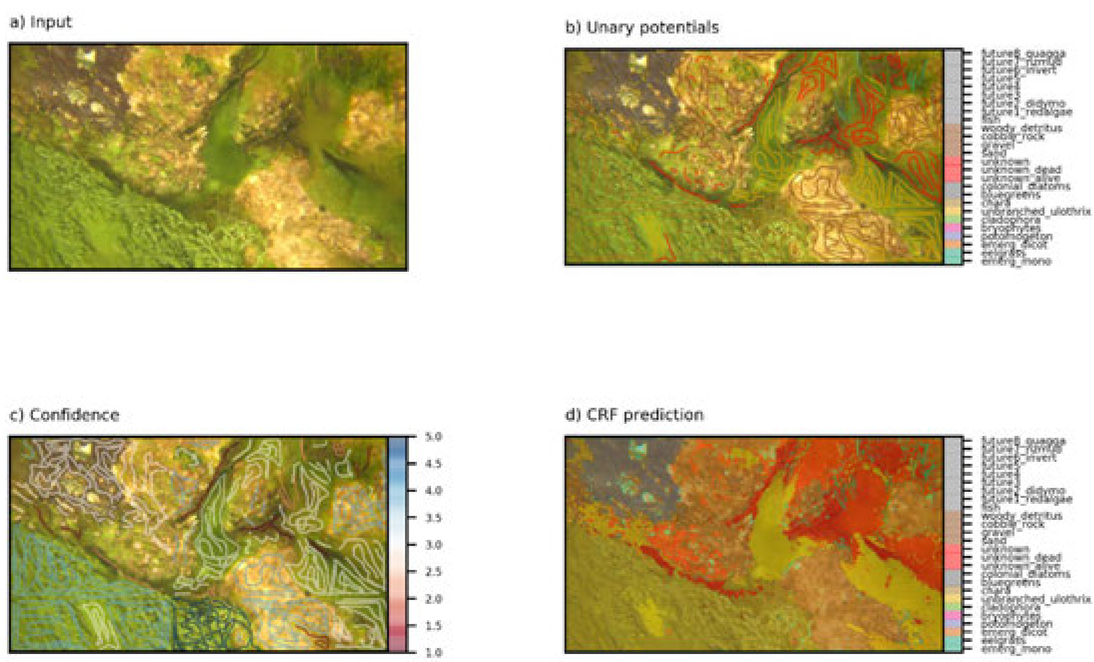

Figure 7. a) Underwater image taken in Lees Ferry (i.e., the input file); b) Manual on-screen image annotations in Python that classify vegetation types at the pixel level (i.e., unary potentials); c) Confidence assigned to each unary potential by the manual annotator in "b"; and d) Predictions of vegetation cover classes using conditional random fields (CRF), a classification and graphical modeling technique.

In FY 2019 we developed a cloud computer workspace to simplify image processing; however, we struggled to get the code to function within the cloud workspace. An alternative workflow was developed from 2019-2020 that will use image polygon annotations in JSON format in the 'Make Sense' webtool (https://www.makesense.ai/) to create image labels and continue to develop a library of images. Images and model refinement continued in FY 2020. This model will ultimately be used to automatically classify thousands of underwater images from annual sampling events and develop a monitoring program to detect change in the CRe over time.

In addition to model development, we selected two permanent reaches of the Colorado River in Glen Canyon that will be used as baseline reaches to detect future aquatic vegetation change. From June 10-13, 2019 we collected approximately 30,000 images of aquatic vegetation, split between the upper reach (~-13 RM) and lower reach (~-4 RM). The upper reach was split into two sections, while the lower reach was split into three sections based on river hydrology and geomorphology. Within each section a piece of equipment adapted from the geomorphology field called the "flying eyeball" (Chezar and Rubin, 2004) captured images along transects running parallel to river flow spaced ~25 m apart. Analysis of those images and refinement of this tool is currently ongoing and will continue into the FY 2021-23 work plan.

Sub-element E.2.3.

The purpose of this project is to use artificial stream experiments to study how aquatic vegetation and higher trophic levels may respond to elevated temperatures in Glen Canyon coming from potential future lower Lake Powell levels. The original study design described in the FY 2018-20 Triennial Work Plan included placing artificial streams adjacent to the Colorado River, but due to permitting issues we set up the artificial stream tanks near the NPS Water Treatment Plant and Maintenance Shop in Lees Ferry. Even though the 12 recirculating stream tanks were fed by water coming directly from the Colorado River through underground pipes ~200 meters away, tank temperatures varied significantly more than the mainstem Colorado River (Δ3 °C) due to underground heating combined with aboveground solar radiation and high summer air temperatures. Even with the most drastic temperature reduction strategies, water temperatures fluctuated by 10 °C daily in May and 7 °C daily in October (Figure 8). As such, the research setup at the NPS facility could not produce results directly applicable to the management of the Colorado River ecosystem as originally envisioned in the FY 2018-20 Triennial Work Plan. Due to a lack of alternate options for artificial stream placement in Lees Ferry we decided the only low-cost option was to move the tanks back to Flagstaff and answer research questions in a controlled laboratory setting at the U.S. Forest Service, Rocky Mountain Research Station.

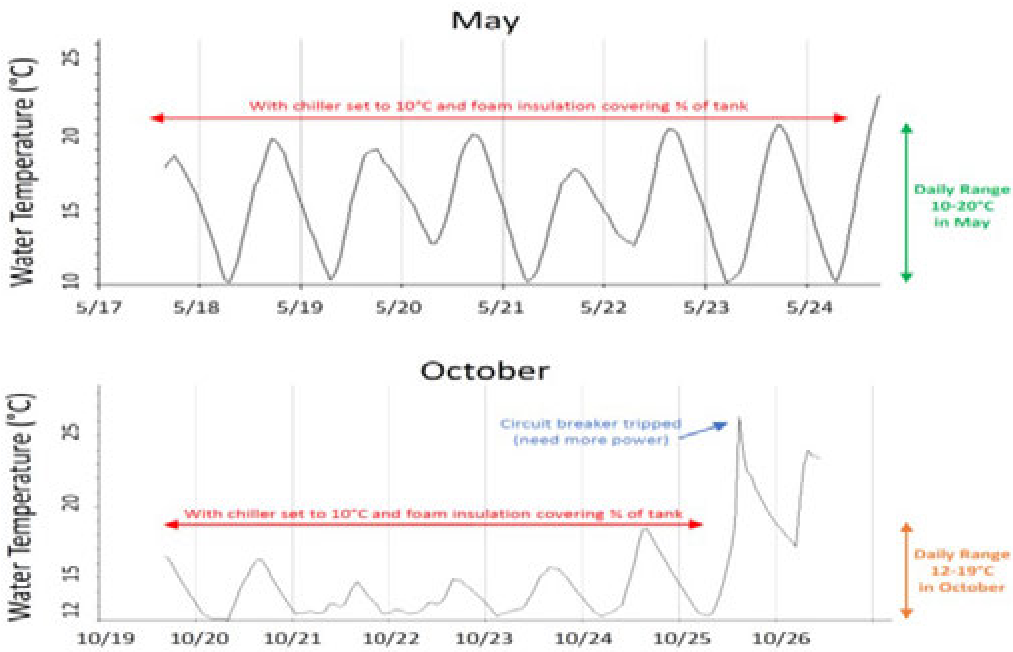

Figure 8. Temperature loggers were placed in tanks having a variety of temperature control mechanisms. These two plots represent the most extreme measures to control temperatures in the tanks, including placing a chiller in each recirculating tank with a foam insulation pad covering ¾ of the tank. Temperatures ranged from 10-20 °C in May (with increasing temperatures reflecting increasing air temperatures as the week progressed) and from 12-19 °C in October. The power grid shorted due to the chillers on 10/26/2018, allowing tank temperatures to increase over the next day until staff drove to Lees Ferry to remove the loggers.

In FY 2019 we modified our study design to simulate river conditions to the extent possible in a laboratory setting, posing the following questions: 1) how does gpp change in response to cold (10 °C), cool (15 °C), and warm (20 °C) temperature treatments over time? 2) what diatom and soft-bodied algal taxa dominate under the three thermal conditions? 3) how might the population dynamics of grazers (i.e., New Zealand mudsnails) respond to temperature treatments as measured by changes in growth, survival, and reproduction? 4) what effect do grazers have on gpp under various warming scenarios? and, 5) to what extent do native, endangered fishes (humpback chub, flannelmouth sucker) consume mudsnails?

In June 2019 we collected cobble, algae, mudsnails, and water from the Colorado River to inoculate 12 replicate artificial stream tanks at the Rocky Mountain Research Station in Flagstaff. Artificial streams were located in an air temperature-controlled greenhouse to reduce variability in water temperatures. Each 150-gallon capacity tank was filled to approximately 100 gallons and a recirculating pump simulated flow within each tank; filters were removed to keep nutrient concentrations consistent. To stimulate biological activity, each tank was inoculated with 1 L of algal slurry containing the dominant algal taxa in Lees Ferry (e.g., *Cladophora*, *Ulothrix*, etc.).

Approximately 10 dry cobbles were placed in each of three baskets (~500 µm mesh size) per tank. One basket contained cobble only and acted as a control; the other two baskets were seeded with 40 mudsnails in two size classes (small ~0.5-1.18 µm, large >1.18 µm). Nine 5.1 x 5.1 cm ceramic tiles were placed in each raceway to track changes in gpp over a 4-5-month period and to examine diatom and soft-bodied algal communities at the conclusion of the experiment. Colorado River water was replaced in a half-tank water change every 2-3 weeks to maintain nutrient levels. Heaters and chillers set to 10, 15, and 20 °C worked in tandem to create desired thermal conditions.

Artificial streams grew from June 21 to November 4, 2019. We removed one of the nine tiles every two weeks and estimated gpp and ecosystem respiration (er) over the course of the experiment using light-dark bottle experiments. At the conclusion of the experiment, we preserved the last tile in 3% Lugol's Solution for analysis of diatom and soft-bodied algal communities. We conducted whole-tank gpp experiments using the cobble from each basket to examine the effect of temperature treatments (Figure 9) and mudsnail grazing on gpp. A separate light experiment was conducted on November 12, 2019 to determine whether light levels varied by area of the greenhouse.

1) Experimental set-up in laboratory

2) Whole-tank gpp experiment

3) Mudsnails in baskets

4) Algae growing on cobble after five months

Figure 9. Artificial stream experiment at the Rocky Mountain Research Station in Flagstaff. 1) Experimental setup with recirculating tank, baskets of cobble with mudsnails (control, small, large snails), and gpp tiles; 2) Whole-tank gpp experiment with cobble from each basket, incubated for 18+ hours in water bath, with continuous reading O_2 mini-dot sensor; 3) Cobble with mudsnails; and 4) Algal growth after five months in artificial stream (June-November 2019).

We have preliminary results for the five research questions posed in this project, but analyses are still ongoing and need further exploration. Across the three temperature treatments in this study, gpp was consistently low in the 10 °C tanks but higher and more variable in the 15 °C and 20 °C treatments (Figure 10a). Similar to gpp, er plots indicate low biological activity in the coldest artificial streams whereas there was a higher but more variable level of respiration occurring in the 15 °C and 20 °C at night (Figure 10b).

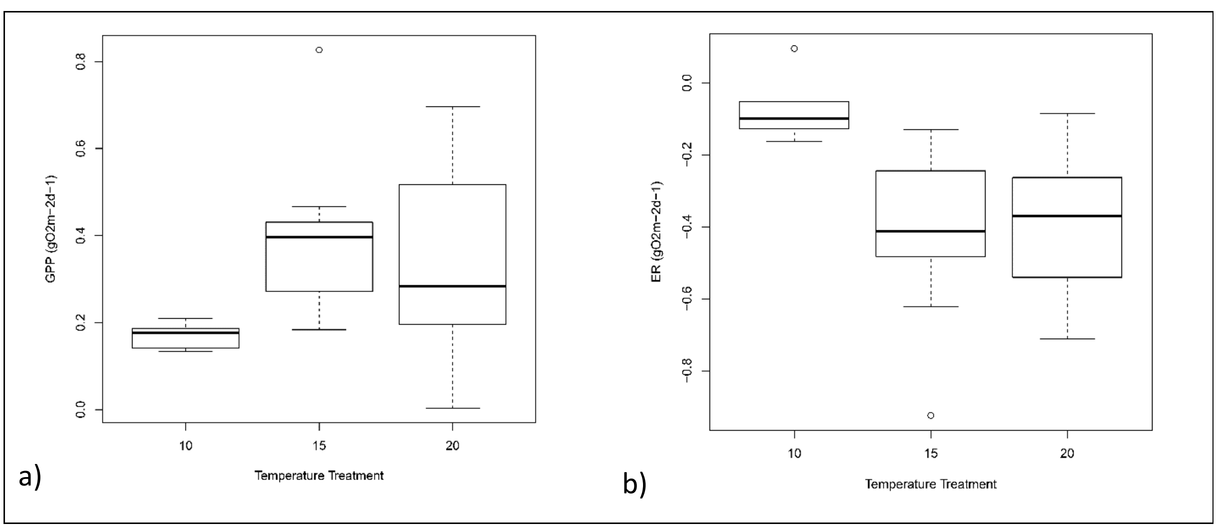

Figure 10. a) Gross primary production (gpp; $gO^2m^{-2}d^{-1}$) and b) Ecosystem Respiration (ER; $gO^2m^{-2}d^{-1}$) in the four replicate tanks per 10, 15, and 20°C treatment.

Differences in gpp and er are likely related to the biomass of diatoms and soft algal species that grew in warmer temperature treatments. There were also differences in diatom and algal diversity that grew in artificial streams on ceramic tiles, with a larger number of diatom species in the 20 °C treatment and the lowest number of species in the 10 °C treatment. Total diversity of soft algal species was similar across temperature treatments, but taxa differed (Table 1). In future analyses, we will be identifying which of these diatom taxa have an upright (vs. adnate) morphology, which is hypothesized to provide a more accessible food source for invertebrate taxa.

Table 1. Diatom and soft algal species that colonized 5.1 x 5.1 cm ceramic tiles over a 5-month period in artificial stream tanks grown at multiple temperature treatments in the laboratory.

Diatom Species	**Division**	**10°C**	**15°C**	**20°C**	**Diatom Species, cont.**	**Division**	**10°C**	**15°C**	**20°C**
Achnanthidium cf. gracillimum	Bacillariophyta			X	Nitzschia perminuta	Bacillariophyta			X
Achnanthidium minutissimum	Bacillariophyta			X	Nitzschia sp.	Bacillariophyta	X	X	X
Achnanthidium sp.	Bacillariophyta	X	X	X	Pinnularia sp.	Bacillariophyta		X	X
Amphora sp.	Bacillariophyta		X		Planothidium lanceolatum	Bacillariophyta	X		
Asterionella formosa	Bacillariophyta		X	X	Planothidium potapovae	Bacillariophyta		X	
Cocconeis pediculus	Bacillariophyta	X	X	X	Planothidium sp.	Bacillariophyta	X		X
Cocconeis placentula	Bacillariophyta	X	X	X	Pseudostaurosira brevistriata	Bacillariophyta	X		X
Cocconeis sp.	Bacillariophyta			X	Pseudostaurosira parasitica	Bacillariophyta			X
Craticula sp.	Bacillariophyta			X	Pseudostaurosira sp.	Bacillariophyta		X	
Craticula subminiscula	Bacillariophyta	X		X	Rhoicosphenia sp.	Bacillariophyta	X		
Ctenophora pulchella	Bacillariophyta	X			Staurosira venter	Bacillariophyta		X	
Cyclotella meneghiniana	Bacillariophyta	X	X	X	Staurosirella pinnata	Bacillariophyta		X	
Cyclotella sp.	Bacillariophyta	X	X	X	Stephanodiscus sp.	Bacillariophyta			X
Cymbella affinis	Bacillariophyta	X		X	Tabularia sp.	Bacillariophyta		X	
Cymbella mexicana	Bacillariophyta	X			Tryblionella sp.	Bacillariophyta			X
Denticula sp.	Bacillariophyta	X	X	X	Ulnaria cf. obtusa	Bacillariophyta		X	
Diatoma moniliformis	Bacillariophyta		X		Ulnaria delicatissima	Bacillariophyta	X		X
Diatoma vulgaris	Bacillariophyta			X	Ulnaria sp.	Bacillariophyta	X	X	
Diploneis elliptica	Bacillariophyta	X			Ulnaria ulna	Bacillariophyta	X	X	X
Encyonema sp.	Bacillariophyta		X	X	Total (Diatom)		27	34	37
Epithemia gibba	Bacillariophyta		X	X					
Epithemia spp.	Bacillariophyta		X		**Soft Algal Species**	**Division**	**10°C**	**15°C**	**20°C**
Fragilaria crotonensis	Bacillariophyta		X	X	Cosmarium sp.	Chlorophyta	X	X	X
Fragilaria sp.	Bacillariophyta	X	X	X	Crucigenia sp.	Chlorophyta	X		
Fragilaria tenera	Bacillariophyta		X	X	Desmodesmus communis	Chlorophyta	X	X	X
Gomphonema cf. parvulum	Bacillariophyta		X		Euastrum sp.	Chlorophyta		X	
Gomphonema cf. sierranum	Bacillariophyta		X		Oocystis sp.	Chlorophyta	X	X	X
Gomphonema parvulum	Bacillariophyta	X		X	Pediastrum duplex	Chlorophyta			X
Gomphonema sp.	Bacillariophyta	X	X	X	Sphaerocystis schroeteri	Chlorophyta			X
Gomphonema truncatum	Bacillariophyta	X	X	X	Stigeoclonium sp.	Chlorophyta	X	X	X
Hannaea sp.	Bacillariophyta	X			Ulothrix sp.	Chlorophyta	X	X	X
Lindavia intermedia	Bacillariophyta	X			Plagioselmis lacustris	Cryptophyta	X	X	X
Melosira sp.	Bacillariophyta	X			Plagioselmis nannoplanctica	Cryptophyta	X		
Navicula antonii	Bacillariophyta		X	X	Rhodomonas lacustris	Cryptophyta		X	
Navicula sp.	Bacillariophyta		X	X	Calothrix sp.	Cyanobacteria	X	X	X
Nitzschia cf. desertorum	Bacillariophyta		X		Chroococcus sp.	Cyanobacteria	X	X	
Nitzschia cf. filiformis	Bacillariophyta			X	Leptolyngbya sp.	Cyanobacteria	X	X	X
Nitzschia cf. fonticola	Bacillariophyta		X		Microcystis sp.	Cyanobacteria			X
Nitzschia linearis	Bacillariophyta			X	Mallomonas sp.	Ochrophyta		X	
Nitzschia palea	Bacillariophyta	X	X	X	**Total (Soft Algal)**		**11**	**12**	**11**

Through our artificial stream experiment, we also explored the question of whether and to what extent native fishes (humpback chub, flannelmouth sucker) are able to effectively consume mudsnails. Mudsnails are found in high densities in Lees Ferry and downstream in the CRe and are hypothesized to alter aquatic food webs. They provide little to no nutritional value when passed whole through the gut of trout species. However, with their pharyngeal teeth flannelmouth sucker and humpback chub are hypothesized to be able to crush mudsnails and gain nutritional value from them as a food source. To answer this question, we partnered with a local high school student from BASIS-Flagstaff who did a senior capstone project in our laboratory. Using nine tanks incubated at 20 °C, 100 mudsnails and four flannelmouth sucker, four humpback chub, or no fish (control) were placed in each of three replicate tanks. Results indicate both flannelmouth sucker and humpback chub find and consume mudsnails, with significantly fewer snails remaining after a 2-week period than the control tanks that lacked fish (Figure 11).

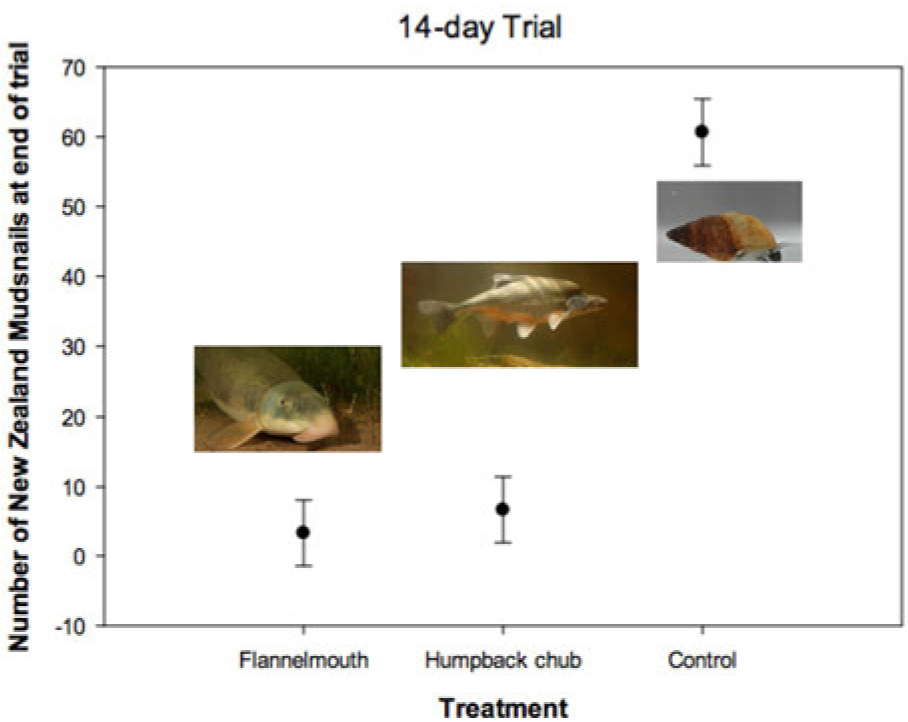

Figure 11. Experiment led by a BASIS-Flagstaff High School Student to determine whether flannelmouth sucker (*Catostomus latipinnis*) and humpback chub (*Gila cypha*) can utilize New Zealand mudsnails as a food source by crushing the snails with their pharyngeal teeth. Figure from Nelson and others, 2020.

Sub-element E.2.4.

The purpose of this project is to link information about patterns in riverine nutrients, temperature, and primary production to higher trophic levels. During early FY 2019, the lead PI (Charles Yackulic) participated in a National Science Foundation-funded workshop and helped develop a conceptual basis for dynamic ecosystem models that use high frequency measurements of gpp. The paper developed from this workshop is published in the journal Limnology and Oceanography Letters (Rüegg and others, 2020). This work was entirely funded outside of the GCDAMP. We are currently working to turn this conceptual model into a statistical model that links gpp, invertebrate drift, and fish population data that are routinely monitored at a few fixed sites in the river. Progress has been slower than desired primarily because of the overall underfunding of modeling in the current work plan, which has required reducing staff and taking on additional outside projects to maintain staff that were only partially funded.

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Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$187,142	$6,000	$36,497	$10,000	$0	$31,976	**$271,615**
Actual Spent	$176,846	$3,803	$20,146	$12,000	$0	$28,058	**$240,853**
(Over)/Under Budget	**$10,296**	**$2,197**	**$16,351**	**($2,000)**	**$0**	**$3,918**	**$30,762**
FY19 Carryover	**$91,973**					**FY20 Carryover**	**$122,735**

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

- Lower costs in salaries was due to a vacancy. Work was accomplished through a cooperative agreement.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to the lack of monsoon storms and associated tributary flooding which led to the cancellation of planned field sampling and in turn eliminated the need to purchase field supplies or pay for sample analyses.

Project F: Aquatic Invertebrate Ecology

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Summary

The principal goal of our work this year was to track invertebrate population response to the third year of the Bug Flow experiment that was tested from May-August 2020. The Macroinvertebrate Production Flow (hereafter, Bug Flow) hydrograph was designed in collaboration with Western Area Power Administration (WAPA) and Bureau of Reclamation staff. COVID restrictions and closure of the river affected our ability to monitor Bug Flows in 2020. Specifically, citizen science light trapping on river trips did not start until June 16 and the spring monitoring river trip that usually occurs in April was delayed until July. The lack of canyon-wide citizen science light trapping on river trips during the spring was partially compensated for by daily light trapping at a single site at the Phantom Ranch boat beach by two dedicated volunteers. Monthly drift and insect emergence monitoring in Glen Canyon occurred as usual without any gaps. Additionally, we continued food base data collections in reaches where humpback chub populations appear to be growing (see Project G) and we collected data to understand the food web effects of trout removal and humpback chub reintroduction in Bright Angel Creek.

Goals and Objectives

Research and monitoring of invertebrates described in Project F informs the Long-Term Experimental and Management Plan (LTEMP; US DOI, 2016) 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 both species of fish. Project F also integrates and uses data from other projects, particularly Project A (streamflow, water quality, and sediment transport), to identify how changing environmental conditions affect invertebrate populations.

Science Questions Addressed & Results

In FY 2020 our group worked with the Bureau of Reclamation and WAPA to design and implement the hydrograph for the Bug Flows experiment (LTEMP Planning/Implementation Team, 2020). This included deciding the appropriate flow level for weekend steady flows for each month of the experiment and routing these flows throughout Grand Canyon to predict how they would affect stage change at various locations of management interest, such as Lees Ferry and the confluence of the Little Colorado River. Bug Flows were tested every weekend from May through August of 2020.

To quantify the effects of Bug Flows in 2020, we launched two Grand Canyon river trips (July and September). The objective of the July trip was to collect light traps across a range of sites in Grand Canyon, to collect drift at juvenile humpback chub monitoring locations (Little Colorado River confluence and Fall Canyon), to deploy dissolved oxygen sensors (Mini-DOTs) for monitoring gross primary production (in support of Project E), and to collect water samples from the mainstem and tributaries for phosphorus and nutrient analyses (also in support of Project E). On the September trip, our objective was to quantify invertebrate drift concentrations approximately every four miles throughout Glen, Marble, and Grand Canyons and to identify whether Bug Flows increased the baseline abundance of drifting midges and other taxa compared to similar, pre- and during-Bug Flow drift data that were collected annually in 2017-2019.

Citizen science light trapping of adult aquatic insects has been ongoing since 2012 (Kennedy and others, 2016), and this dataset is critical to evaluating food base response to the Bug Flow experiment. These data indicate aquatic insects responded strongly and positively during the first year of Bug Flow testing in 2018. Specifically, the abundance of caddisflies increased by around 400% in 2018, concurrent with Bug Flow testing, compared to pre-Bug Flow years (2012-2017; Figure 1). Caddisfly abundance returned to baseline levels in 2019 during the second year of Bug Flow testing. However, the timing of caddisfly emergence was much later in 2019 compared to 2018 (Figure 2). In fact, caddisfly emergence did not peak until August 13, roughly 1.5 months later than in 2018 and the latest in the 8-year citizen science light trap record (Figure 2). Midges followed a similar pattern with early emergence in 2018 and late emergence in 2019. The timing of insect emergence is an indicator of growing conditions, with early emergence being an indicator of favorable growing conditions while late emergence indicates poor growing conditions. Thus, growing conditions were likely quite poor in 2019. The poor growing conditions in 2019 appear to have been caused by unusually turbid water in the Colorado River in spring (Figure 3). High turbidity reduces rates of algae production and interferes with insect feeding. Vastly different growing conditions during the first two years of the Bug Flow experiment complicate interpretation of monitoring data (LTEMP Planning and Implementation Team, 2020).

In 2020, citizen science sampling yielded 510 light traps. These 2020 light trap samples are fully processed as of November 15, 2020 and will be analyzed and interpreted for our Annual Reporting Meeting presentation in January 2021. Citizen scientists also collected acoustic bat activity data paired with half of these light trap samples. These paired data will be used to identify whether there is a correlation between aquatic insect abundance and bat activity levels throughout the Colorado River corridor in Grand Canyon.

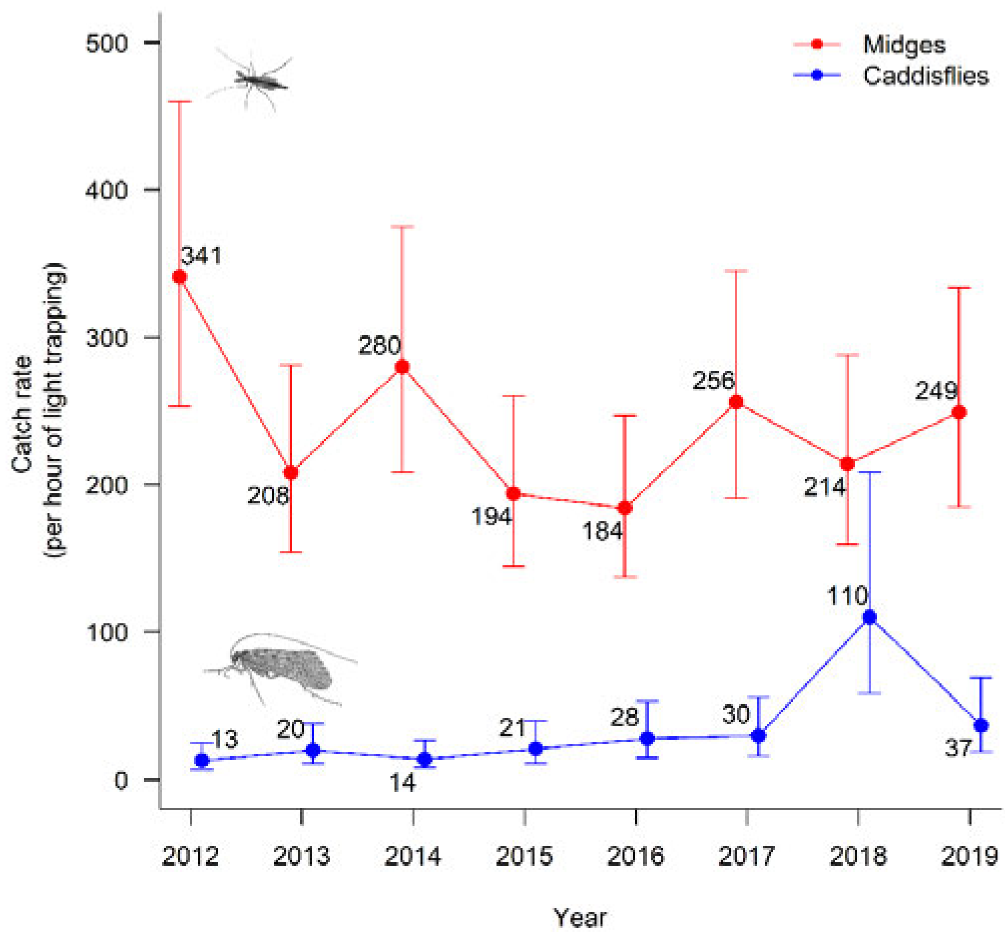

Figure 1. Average midge and caddisfly abundance in citizen science light traps over time, including the first two years of Bug Flows experimentation in 2018 and 2019. Error bars represent one standard error. Annual average values are estimated from a mixed-effects model that accounts for the underlying distribution of the data (negative binomial). These models also account for differences in the spatial or temporal extent of sampling across years. Caddisflies are in the Order *Trichoptera*, which is part of the sensitive "EPT" group.

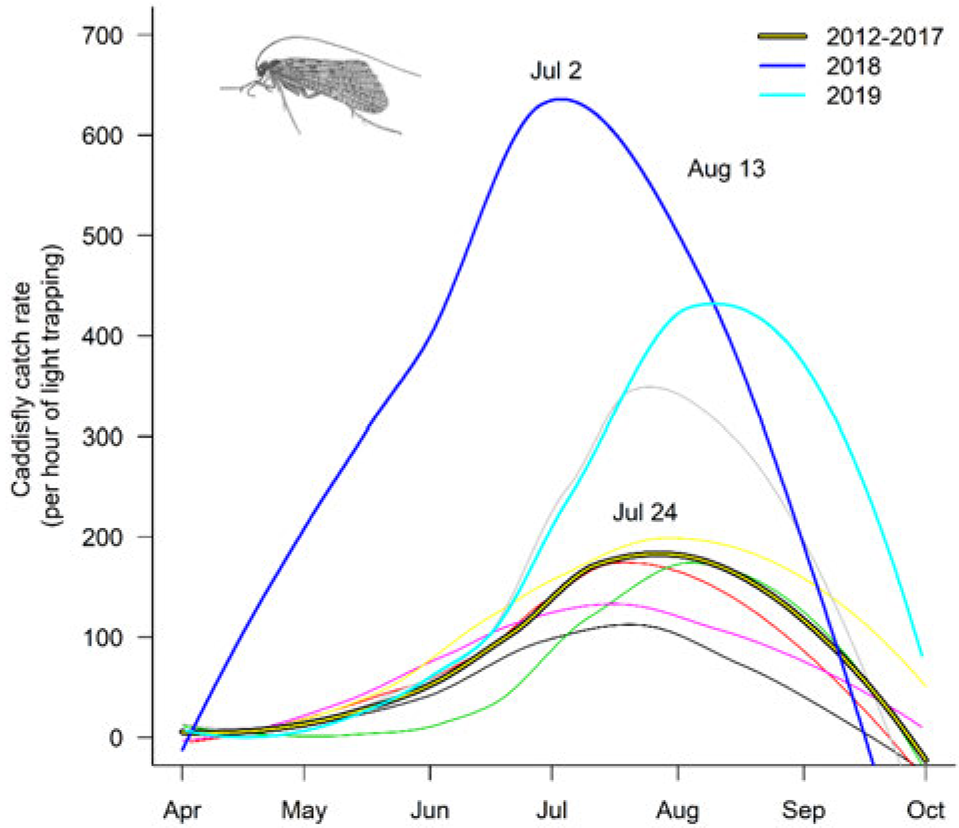

Figure 2. Graph showing the seasonal pattern of caddisfly emergence from 2012-2019. Peak emergence of caddisflies in 2019 during the second year of Bug Flow testing was 1.5 months later than in 2018 during the first year of Bug Flow testing. The timing of insect emergence is an indicator of growing conditions, with early emergence indicating good conditions and late emergence indicating bad conditions.

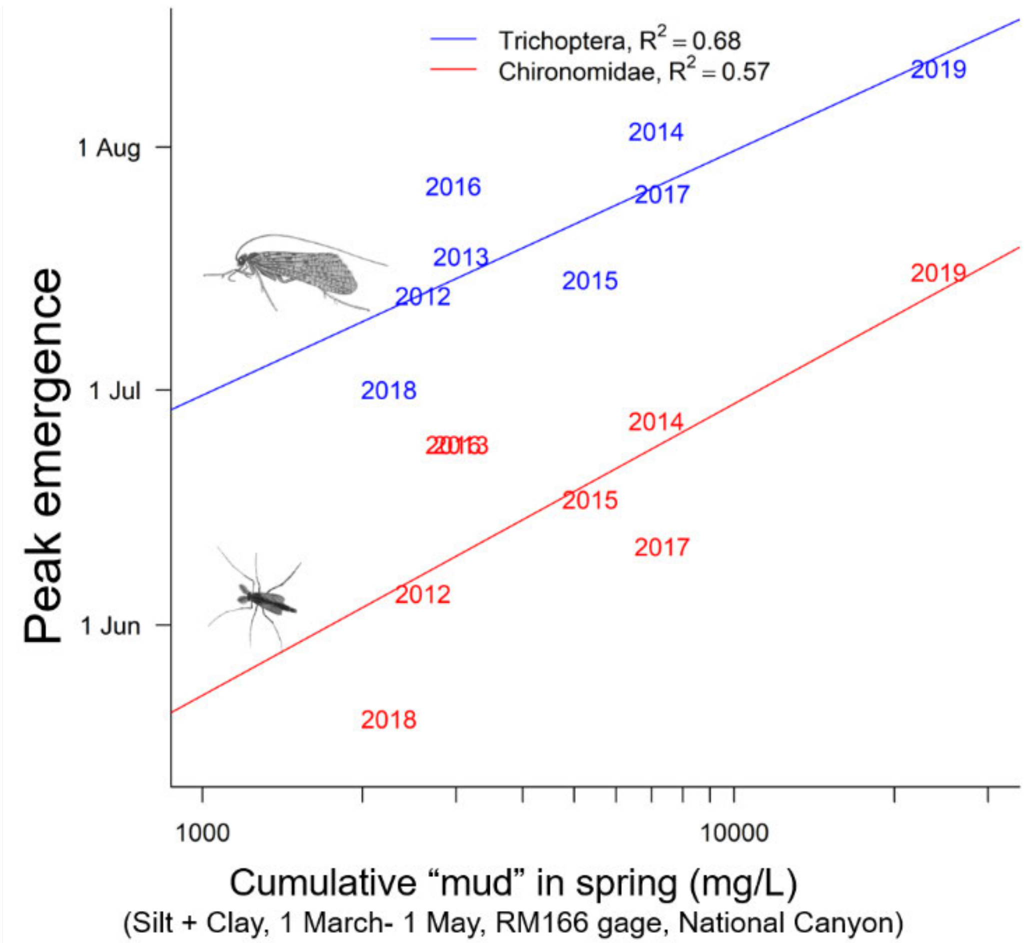

Figure 3. Relationship between midge and caddisfly adult activity (emergence timing) and springtime suspended sediments (Colorado River above National Canyon gage, aggregated 15-minute data, period of record March 1-May 1). Springtime sediment is inversely related to growing conditions for aquatic insects. Note that base environmental conditions were “good” in 2018 (low sediment) and “bad” in 2019 (high sediment, nearly 10X greater than in 2018), irrespective of the Bug Flows experiment. R^2 values are the ‘coefficient of determination’ and represent the proportion of variance in emergence timing (Y-axis) that is explained by the amount of mud during spring (X-axis).

Our group continued long-term monitoring of the aquatic food base in the Lees Ferry sport fishery (Metcalfe and others, 2020). This monitoring includes monthly drift, sticky trap, and light trap sampling from Glen Canyon Dam (RM -15) to Badger Rapid (RM 8). Sample processing for all Lees Ferry data collections is current. As part of our monthly sampling in Lees Ferry, we also re-calibrated and serviced dissolved oxygen monitoring instruments, which provide data used in modeling algae production in the Colorado River (see Project E). Collectively, these data collection efforts will allow us to assess invertebrate population response to Bug Flows and track the status and trends of the aquatic food base across a variety of sampling methods and on robust spatial and temporal scales.

Analysis of these data is ongoing. A presentation on status and trends of the food base in Lees Ferry, including whether there is evidence of a Bug Flow effect, will be part of the Annual Reporting Meeting in January.

In response to a request from the National Park Service, our group continued studies of the food base in Bright Angel Creek associated with ongoing trout removal efforts and the reintroduction of humpback chub in 2019. Our sampling approach is based on the design used by Whiting and others (2014) that was used to sample aquatic invertebrates in Bright Angel Creek prior to trout removal. We sampled aquatic invertebrates in Bright Angel Creek four times in FY 2020 (November 2019 and January, June, September 2020). In total, we collected 48 benthic, 36 drift, and 48 sticky trap samples of aquatic insects in the 3200 m reach upstream from the mouth of Bright Angel Creek. We have been conducting these quarterly sampling trips since 2016, and now have a dataset that spans multiple years of trout removal in addition to humpback chub reintroduction. This work will allow us to explore how the food web 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 and will be submitted to a journal in FY 2021.

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Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$547,192	$20,316	$30,244	$0	$0	$82,454	**$680,206**
Actual Spent	$683,113	$9,454	$44,940	$0	$0	$101,732	**$839,239**
(Over)/Under Budget	**($135,921)**	**$10,862**	**($14,696)**	**$0**	**$0**	**($19,278)**	**($159,033)**
FY19 Carryover	**($7,534)**					**FY20 Carryover**	**($166,567)**

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

- Higher costs for salary were due to the need for additional staff and increased overtime as a result of processing of aquatic food base samples from the Bug Flow experiment in 2019 and 2020 including additional samples collected for tasks added to the original study design at the request of cooperators and stakeholders.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs of operating expenses were due to the need to purchase field equipment that had failed.
- The lack of anticipated Experimental Funds in FY2020 constitutes the overall budget shortfall for Project F.

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

Project Lead	Charles B. Yackulic	**Principal Investigator(s)** (PI)	Charles B. Yackulic, USGS, GCMRC Maria Dzul, USGS, GCMRC Michael Yard, USGS, GCMRC Kirk Young, USFWS Randy Van Haverbeke, USFWS David Ward, USGS, GCMRC Laura Tennant, USGS, GCMRC
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Summary

The overall goals of Project G are to accurately estimate the abundance of various life stages of humpback chub to inform triggers associated with the 2016 Biological Opinion (USFWS, 2016), and to improve understanding of humpback chub (*Gila cypha*) life history and its drivers so that we can accurately forecast impacts of management actions on future abundances. To support these goals, humpback chub monitoring focuses on sampling fish from juvenile, subadult, and adult life history stages using mark-recapture analyses whenever feasible. Modeling provides timely and accurate estimates using the data, but also focuses on continually improving our approaches to estimation, determining drivers of population abundance, quantifying the efficacy of existing management actions, and developing tools to forecast impacts of alternative management strategies.

Goals and Objectives

For the FY 2018-20 Triennial Work Plan, humpback chub research included sampling trips to the lower Little Colorado River (LCR), in the juvenile chub monitoring (JCM)-east reach located in the Colorado River near the LCR confluence (62.8-66.0 river miles (RM) downstream of Lees Ferry), and in the JCM-west reach located in the Colorado River near Fall Canyon (RM: 210.5-214.0). The above-mentioned sampling efforts visited the same reaches across trips, and thus powerful mark-recapture analyses are possible. Unfortunately, due to the COVID-19 pandemic and the closure of Navajo lands and Grand Canyon river trips there was no mark-recapture sampling between March and early July 2020. This closure results in a gap in our data collection during spring, which is typically the time when humpback chub are actively spawning and more likely to move long distances. In 2020, we were able to collect some data from the LCR during this time from stationary passive integrated transponder (PIT) tag antennas and results suggest that the number of humpback chub moving into the LCR was roughly similar between 2019 and 2020.

To complement this intensive sampling effort, monitoring also included more widespread sampling of the Colorado River via HBC aggregations and backwater seining trips (the latter of which will cease in the new work plan).

Data collected as part of Project G are regularly used to assess population health of federally endangered humpback chub. Data from US Fish and Wildlife Service (USFWS) LCR monitoring (G.2), USGS LCR monitoring (G.3), and USGS monitoring in the JCM-east reach (G.3) were used to obtain estimates of vital rates (survival, growth) as well as HBC abundances from multistate models (Figure 1) and closed models. These estimates are used to assess Biological Opinion triggers (i.e., trout removals), and these estimates are regularly presented each year at the annual reporting meeting. Additionally, we are working on developing models for adult humpback chub in western Grand Canyon, which seem to regularly move into and out of the JCM-west sampling reach and thus require additional modeling considerations.

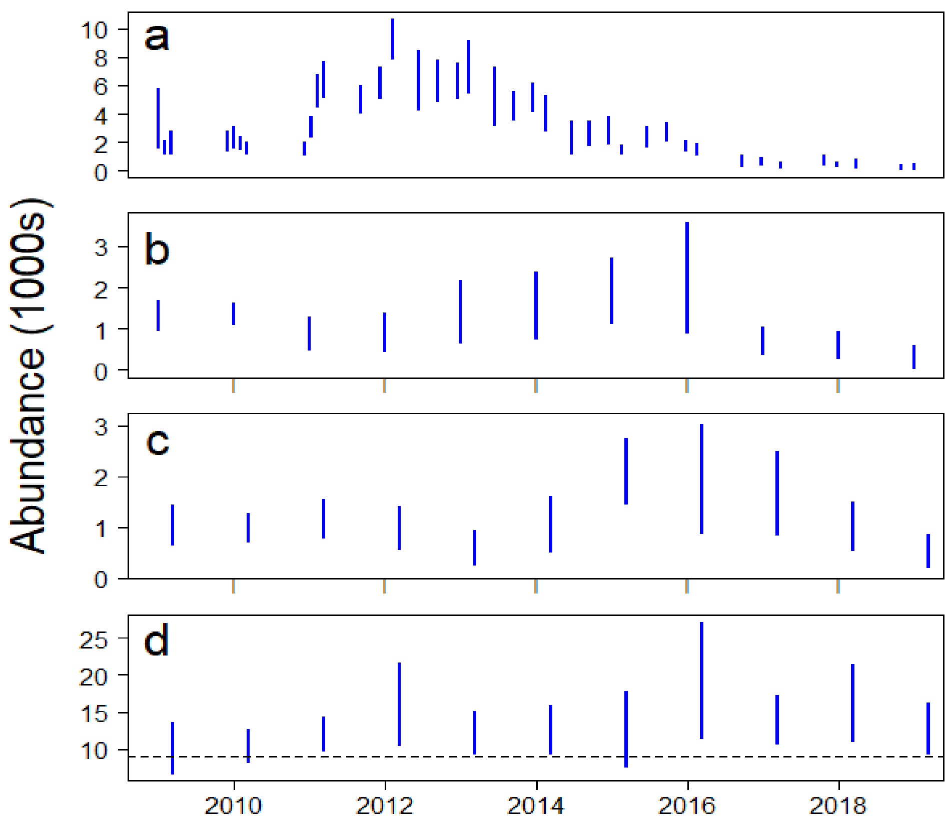


Figure 1. Abundance estimates for four size classes of humpback chub (*Gila cypha*) from 2009-2019. Estimates of juveniles (panel a; <100mm total length; TL), small subadults (panel b; 100-149mm TL) and large subadults (panel c; 150-199mm TL) are for the juvenile chub monitoring reach (JCM-east, RM: 62.8-66.0) whereas estimates of adult humpback chub (panel d; >200mm TL) pertain to all adults that spawn in the LCR. The trigger line (9000) for adults is shown as a dotted line in panel d. The span of the bars represent 95% credible intervals.

Model development as part of this project focused on three areas: 1) developing approaches to integrate multiple data types and provide the best estimates of vital rates (i.e., growth, survival, movement) and abundance, 2) analyzing data to determine the drivers of variation in vital rates, and 3) working to bridge the gap between biological understanding and management decisions in conjunction with project J. In FY 2018-20, progress in area 1 included development of novel statistical models that integrate detections from autonomous PIT antennas with traditional field data in our humpback chub population models (Dzul and others, *in prep*; Dzul and others, *in review*). In addition, we developed approaches that improve the computational efficiency of Bayesian population models by several orders of magnitude, allowing us to more quickly and more accurately analyze humpback chub monitoring data (Yackulic and others, 2020). We also began to develop models using data from JCM-west and this is an ongoing effort. With respect to area 2, Yackulic and others (2018; 2019) quantified the effects of rainbow trout on age-0 humpback chub dynamics in Colorado River (near the LCR confluence) and concluded that rainbow trout do have a moderate negative effect on age-0 humpback chub, but that environmental factors (e.g., temperature and turbidity) can be more important drivers of age-0 dynamics. Similarly, ongoing juvenile monitoring in the LCR has illustrated that age-0 humpback chub production is low in years without winter flooding (Van Haverbeke and others, 2013), a finding that was reinforced by the winter of 2017-2018 which had no floods and resulted in low age-0 production. Lastly, decision-driven research (area 3) during FY 2018-20, was focused on developing cost-effective approaches to trout removal (see Project J) and developing a model to evaluate the effects of USFWS humpback chub translocation above Chute Falls to determine how many extra juveniles recruit to adulthood as a result of this action (Yackulic and others, *in review*).

G.1. Humpback Chub Population Modeling

In FY 2018-20, modeling efforts have focused primarily on describing humpback chub population dynamics in the LCR aggregation (i.e., for all humpback chub that spawn in the LCR), though one model was developed as part of an initial assessment of humpback chub population dynamics in western Grand Canyon. Models of humpback chub in the LCR aggregation are all fit to mark-recapture data and include the following progress during this work plan: 1) development of a more efficient model-fitting approach (i.e., marginalization) that allows for fitting more complex models with random effects (Yackulic and others, 2020). This approach is now used for annual updates of the humpback chub multistate model for the LCR aggregation, but also forms the backbone of the brown trout (*Salmo trutta*) and JCM-west population models being used for annual updates, 2) development of a model that utilizes antenna array detections in the LCR to evaluate spawning dynamics and alternative life histories in humpback chub (Dzul and others, *in review*), 3) development of an approach to integrate submersible PIT antenna detections into our regular analyses to improve abundance estimation of adults in the

LCR aggregation (Dzul and others, *in prep*), 4) publication of model evaluating drivers of age-0 humpback chub dynamics in the JCM-east reach (Yackulic and others, 2018) and a fact sheet summarizing this work (Yackulic and Hull, 2019), and 5) an evaluation of the efficacy of USFWS translocations in terms of their estimated impact on overall adult abundance in the LCR aggregation including a comparison of the cost effectiveness of trout removals to translocations above Chute Falls (Yackulic and others, *in review*). In progress analyses focus on better quantifying juvenile production and outmigration from the LCR and developing a mark-recapture model for fish in western Grand Canyon.

Yackulic and others (2020) describes an efficient model-fitting method (marginalization) and provides examples of how this type of model fitting can used to improve the speed of Bayesian models. One of the applied examples evaluates how marginalization has benefitted estimation of humpback chub vital rates (e.g., survival, growth, movement). Specifically, previous models of humpback chub in the LCR aggregation would either have to assume that rates were temporally constant (e.g., survival is the same every year), or that rates between years are completely different. When rates are considered completely different across years, the resulting confidence intervals are very wide and this limits inference. The marginalization approach developed allows for survival rates to be pooled across years, while also allowing for years to have different values, and this in turn allows for rates to differ across years but with better precision.

Dzul and others (*in review*) uses antenna detections to evaluate survival and growth differences in alternative life history strategies of humpback chub. Incorporation of antenna detections provided insight about humpback chub movement dynamics and survival rates. Specifically, the model found that a large proportion of Colorado River migrants were detected on antennas but not captured by the USFWS during their spring monitoring trips, suggesting either that there is a mismatch in the timing of USFWS sampling and humpback chub movement or that adult chub are trap-shy and do not enter hoop nets. Also, the model estimated higher survival rates when antennas were included compared to when antennas were not included. One goal of this model was to identify costs associated with Colorado River humpback chub migration into the LCR (presumably a spawning migration). Results indicated that survival and growth rates were similar for Colorado River fish regardless of whether or not they had migrated into the LCR that year, suggesting migration costs may be low or that there are feeding/growth benefits to being in the LCR during spring. The model also estimated low over-winter survival rates for LCR residents (i.e., adults that reside in the LCR year-round) and suggests over-winter residents may have a shorter lifespan than Colorado River migrants. Lastly, the model found some evidence for heterogeneity in movement rates in large females and did not find any large costs to survival or growth associated with movement.

Dzul and others (*in prep*) describes an extension of the multistate model first developed in Yackulic and others (2014). This multistate model is important for decision-making because it is regularly used to obtain abundance estimates of humpback chub for annual reporting and inform biological triggers. In FY 2018-20, this model was been modified to include PIT tag detections from submersible antennas in the JCM-east reach. Because antennas improve detection of adults (which tend to have low capture probabilities), abundance estimates from models with antennas have better precision compared to models without antennas (Figure 2). Model development and results are included in a manuscript that describes how to use PIT antenna detections in abundance estimation (Dzul and others, *in prep*).

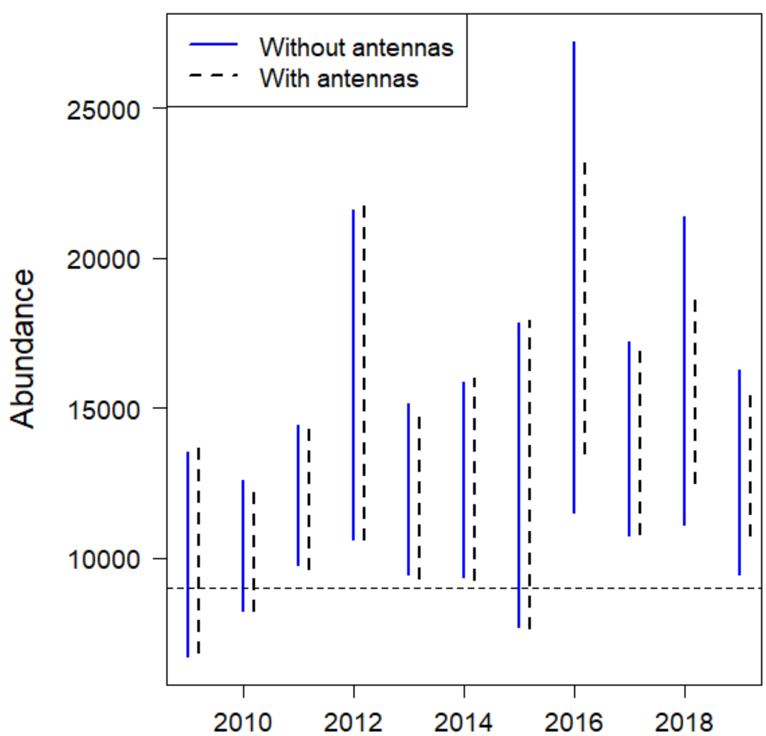


Figure 2. Adult humpback chub abundance estimates from the LCR aggregation. Abundance estimates come from a multi-state model first developed by Yackulic and others (2014) and later modified to allow for year-to-year variability in survival and growth rates (Yackulic and others, 2019). This model includes detections from submersible antennas placed in the Colorado River sampling reach (i.e., JCM-east reach, RM: 62.8-66.0) in 2016, 2018, and 2019. Abundance was estimated from this model using two different methods. The first method did not include antenna detections in the abundance calculation (the 'without antennas' method) and the second method ('with antennas') included antenna detections in abundance estimation by estimating the abundance of marked and unmarked fish separately (Dzul and others, *in prep*).

Yackulic and others (2018) evaluates competing models of juvenile (<100mm TL) humpback chub survival and growth, where models include effects of rainbow trout abundance, water temperature, turbidity, and intraspecific density-dependence. Results indicated that temperature and turbidity had strong positive effects on growth and turbidity had a strong negative effect on survival. To a lesser extent, rainbow trout abundance negatively impacted humpback chub survival and growth. Taken together, results indicate that rainbow trout predation on and competition with humpback chub negatively impacts juvenile humpback chub, but that environmental drivers are likely more important. Also, there was substantial unexplained variability in the model, emphasizing that other unknown factors may be important.

Yackulic and others (*in review*) evaluates the effect of Chute Falls translocations on adult humpback chub abundance. This model estimates vital rates for humpback chub in the Colorado River, in the lower LCR (i.e., river km (rkm) 0-13.56), and the upper LCR (rkm 13.57-17.1). Model results indicate that continuous effort of translocating 200 juvenile HBC each year upstream of Chute Falls would be expected to result in an extra 246 (95% CI: 76-430) adult HBC under equilibrium conditions, compared to no translocations. Importantly, the extra adult HBC produced from translocations decrease the need for more controversial management actions (i.e., trout removal). However, translocations are limited in their potential for increasing adult numbers thus necessitating trout removals in scenarios where humpback chub numbers plummet.

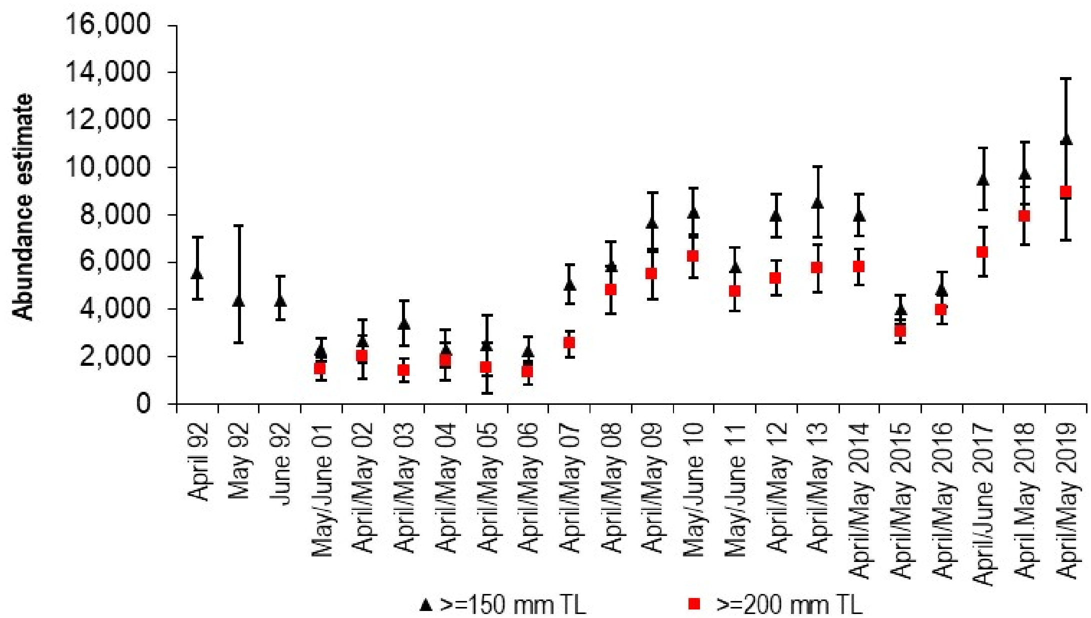
In addition to the above completed, or nearly completed analyses, we have also made progress in two other modeling projects. One project is focused on estimating juvenile production and outmigration from the LCR. We hope that insights about year to year variability in age-0 production and outmigration will help us learn more about which years (and environmental conditions) are conducive towards boosting recruitment, improving our ability to forecast humpback chub dynamics. Lastly, we have made some initial assessments of humpback chub in JCM-west. Preliminary analysis and biologists' observations suggest fish in JCM-west are highly mobile and regularly swim into and out of the sampling reach. Accordingly, we developed a model that uses antenna detections and physical captures (i.e., hoop nets, electrofishing) in a robust design framework to estimate temporary emigration and immigration into the sampling reach. Initial results suggest that survival rates for adults in western Grand Canyon may be lower than survival rates near the LCR. Also, there is some evidence that fish may be more mobile during the spring spawning months. Uncertainty in parameter estimates is high due to the short time from of the study (3 years), low capture probabilities, and the high mobility of fish. We hope that additional years of data collection will help us learn more about population dynamics in JCM-west.

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

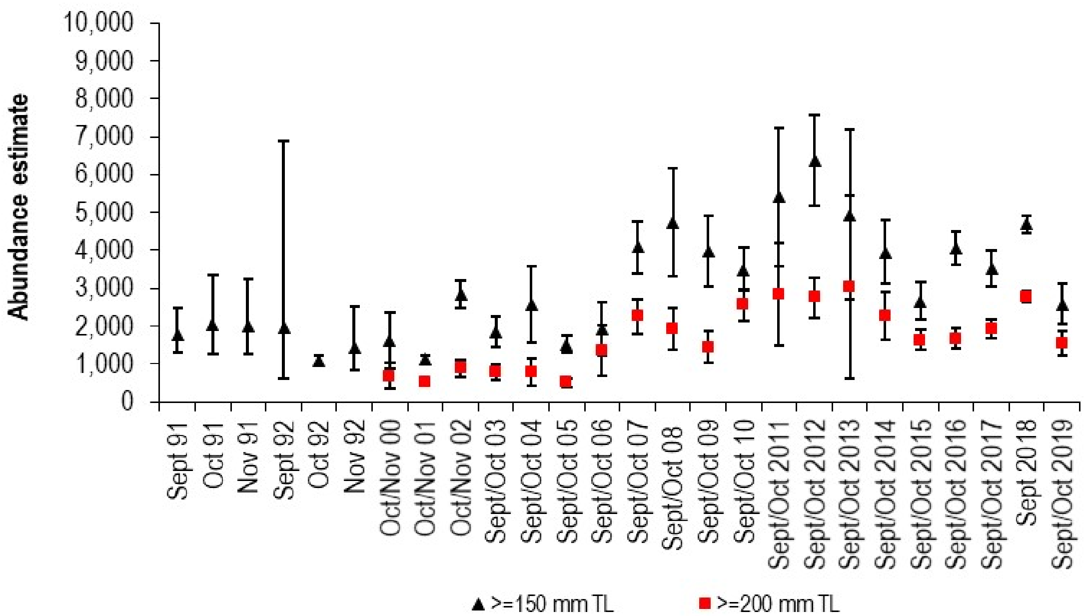
In 2020, USFWS and volunteers conducted two monitoring trips during September and October to monitor humpback chub in the LCR. The goal of these trips was to monitor the population status and trend of humpback chub in the LCR. Because of COVID-19, we were unable to conduct our usual monitoring trips during April and May. As a result, we present below our spring and fall 2019 estimates (fall 2020 estimates are *in prep*). During spring 2019, we estimated that there were 11,210 (Standard Error [SE] = 1,300) humpback chub ≥150 mm total length (TL), of which 8,987 (SE = 1,048) were ≥200 mm TL in the LCR (Figure 3A). These numbers represent the highest spring abundance of humpback chub in the LCR recorded to date.

In fall 2019, it was estimated that there were 2,589 (SE = 275) HBC ≥150 mm TL in the LCR. Of these fish, an estimated 1,545 (SE = 160) were ≥200 mm TL (Figure 3B).

A.



B.



B.

Figure 3A and 3B. 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 (A) spring (2001-2019) and (B) fall seasons (2000-2019). 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).

G.3. Juvenile Humpback Chub Monitoring near the LCR Confluence

In 2020, the May JCM trip was cancelled due to the COVID-19 pandemic and thus there were only two juvenile HBC monitoring trips (occurring in July and October) in the JCM-east site. Two methods (slow-shock electrofishing and hoop nets) were used to capture fish, and eight submersible antennas were also deployed during these trips to supplement electrofishing and hoop netting efforts. All humpback chub > 79 mm TL were marked with PIT-tags, and all humpback chub between 40-79 mm TL were marked using visual implant elastomer (VIE). We caution that data reported here are provisional and have not been fully checked for quality control.

Humpback chub were the most frequently caught species in JCM-east catch (1281), followed by flannelmouth sucker *Catostomus lattipinnus* (487), rainbow trout *Oncorhynchus mykiss* (442), fathead minnow *Pimephales promelas* (247), bluehead sucker *Catostomus discolobus* (119), speckled dace Rhinichthys osculus (82), carp *Cyprinus carpio* (22), yellow bullhead *Ameiurus natalis* (17), plains killifish *Fundulus zebrinus* (9), brown trout (7), striped bass *Morone saxatilis* (4), green sunfish *Lepomis cyanellus* (3), and channel catfish *Ictalurus punctatus* (2). In total, all JCM-east trips captured 895 humpback chub > 79mm TL and marked 311 humpback chub between (40-79 mm TL) with VIE.

Catch of humpback chub >79mm TL was 311 in July and 584 in October. In addition, the number of humpback chub given a VIE mark (between 40-79mm TL) was 58 in July and 253 in October.

Pre-Monsoon Juvenile Chub Sampling in the LCR

The main focus of this trip was to mark and recapture juvenile HBC to obtain an estimate of population size and outmigration. Compared to previous years, this trip was shortened in both spatial and temporal extent due to the COVID-19 pandemic. Specifically, monitoring occurred from July 7-13, 2020 on lands managed by the National Park Service (i.e., the lower 3.6 rkm) due to closure on Navajo lands. Thus, only four of the fifteen subreaches were sampled. The sampling methodology was similar to previous years in that each subreach was sampled for two days (i.e, two passes) and fish were captured using hoop nets and seines. All humpback chub > 39 mm TL and < 80 mm TL were given VIE marks that were specific to the trip, gear type (hoop net versus seine), and size category (40-59 mm TL or 60-79 mm TL). For other fish, the trips followed the fish handling protocol (Persons and others, 2013), except that native fish > 99 mm TL that were captured during the afternoon hoop net hauls were not processed (i.e., they were released immediately without scanning for a tag or obtaining measurements). This change occurred at the direction of USFWS. During this trip, 641 humpback chub (40-79 mm TL) were marked with VIE.

Because only the lower portion of the LCR was sampled, we are working to modify abundance models to include year and site effects. This modification should allow us to extrapolate our 2020 mark-recapture data to an abundance estimate for the entire LCR. Catch data suggest that abundance of age-0 humpback chub was relatively high for 2020, but also very uncertain due in part to the fact that estimates are based on data from only four of fifteen subreaches. When viewed over a longer time scale (2013-2020), it is apparent that age-0 production exhibits high variability from year-to-year, and this likely results in recruitment pulses that occur sporadically. The last two years (2019-2020) have had higher age-0 production compared to the three previous years (2016-2018; Figure 4). Despite these larger production years, outmigration and juvenile abundance in the JCM reach remains low, though it is possible that the 2020 outmigration event has not yet occurred due to the lack of fall monsoon activity.

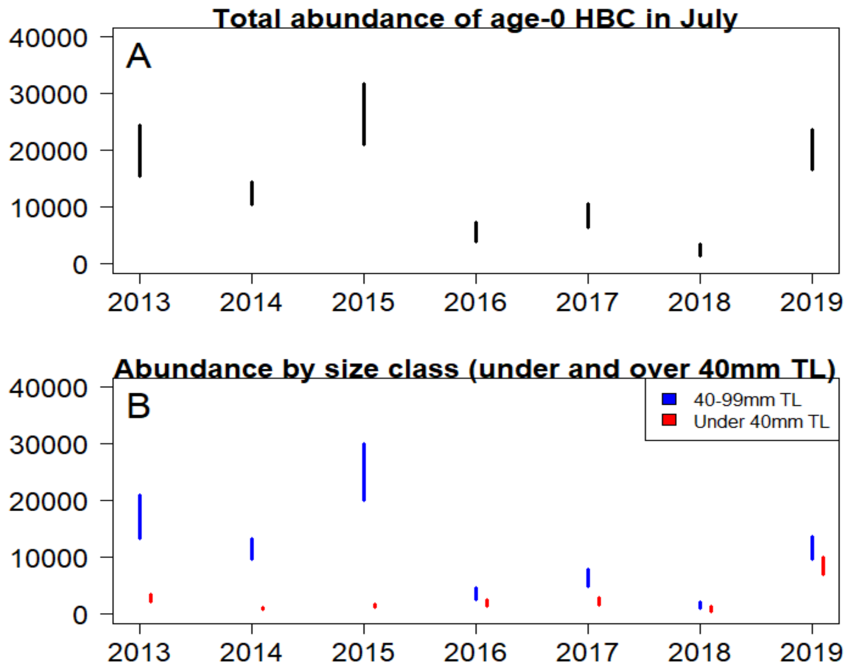


Figure 4. Estimated abundance of age-0 humpback chub (i.e., < 99 mm total length (TL)) during mid-summer sampling trips to the lower 13.6 km of Little Colorado River. Data from 2020 are not included because sampling only occurred in the lower 3.6km of the LCR due to the COVID-19 pandemic.

G.4. Remote PIT-Tag Array Monitoring in the LCR

Remote Technologies

Passive Integrated Transponder (PIT)-tag antennas are placed in aquatic environments to detect PIT-tags of fish that swim by. Antennas produce a continuous stream of data that can provide detailed information about movement timing without requiring fish handling. In the LCR, we use PIT-tag antennas from a multiplexer array (MUX) to detect movements of fishes between the Colorado River and LCR. The LCR MUX is located about 1.7 km upstream of the LCR confluence with the Colorado River and is comprised of two arrays (*in situ* chains of PIT-tag antennas that stretch across the river), an upstream and a downstream array. The LCR MUX had very limited functionality in 2019-2020, as the downstream array was nonfunctional and the upstream array only had 1-2 antennas working during this time. The MUX was scheduled to be replaced in May 2020 but this installation was cancelled due to the COVID-19 pandemic. Fortunately, the new MUX was successfully installed by a crew from Biomark, Bureau of Reclamation, USGS, and Utah State University in early November 2020, and this new MUX should provide improved data in FY 2021. The new MUX was funded by the Bureau of Reclamation outside of the GCDAMP, and Biomark, Inc., was awarded the contract to build the antennas and help with removal of old antennas and installation of new antennas.

In addition to the MUX, a network of 4-8 single, shore-based antennas were first installed in the LCR in 2017 to help supplement MUX detections. The purpose of this antenna network was to replace the MUX; however, when fully functional the MUX detects more fish than the shore-based antenna network. Nevertheless, the shore-based network design has improved in the last two years and it is better designed for assessing movement directionality because there is a relatively large waterfall located between the two antenna clusters which we believe acts as an obstacle that deters fish from continuously swimming over both antenna clusters, over short time intervals. The shore-based antenna network design was operational in 2020 and the design consisted of eight antennas – four were placed near 1.3-1.4 rkm upstream of the LCR confluence with the Colorado River (hereafter the Amazon Island cluster) and four were placed upstream of the waterfall at Boulders camp (rkm 2.0-2.2, hereafter the A-Rock cluster). In contrast to the LCR MUX, these antennas are smaller (e.g., 123 cm x 61 cm) and are placed parallel to the shoreline. Importantly, detections from the antenna network provided the main source of fish detection data over the winter and spring of 2020 when fieldwork was prohibited due to the COVID-19 pandemic. During the 2020 spring migration window (Feb 15 - Jun 15), the shore-based antenna network detected 5004 unique PIT tags, 3921 of which were HBC. Of these 3921 tags, 370 were detected on both the Amazon Island and A-Rock clusters going upstream and 7 were detected on both clusters going downstream. These counts are roughly similar to 2019, when seven antennas were deployed.

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

The primary objectives of the annual HBC aggregation trip is to continue a long-term relative abundance (catch per unit effort, CPUE) index of HBC in the historical "aggregation" sites (Valdez and Ryel, 1995). Since 2017, these trips have been used to conduct closed mark-recapture efforts in discreet sections of the mainstem. These reaches have included both JCM reaches and several reaches below Diamond Creek (Pillow and others, 2018; Van Haverbeke and others, 2020). This is a result of an increasing interest in understanding absolute abundances of HBC in the mainstem Colorado River. Most of these mark recapture efforts have also estimated densities (fish/mile) of flannelmouth sucker.

Considering the historical data, since 2010 the number of overnight hoop nets per trip has remained relatively steady on aggregation trips. However, CPUEs of humpback chub and flannelmouth sucker have increased significantly during this time period (Figure 5). Much of the elevated HBC CPUE values seen in the past few years is a result of higher HBC capture rates in the western Grand Canyon (from the Havasu aggregation downriver), where there has been a dramatic increase of HBC (Figure 6; Van Haverbeke and others, 2017).

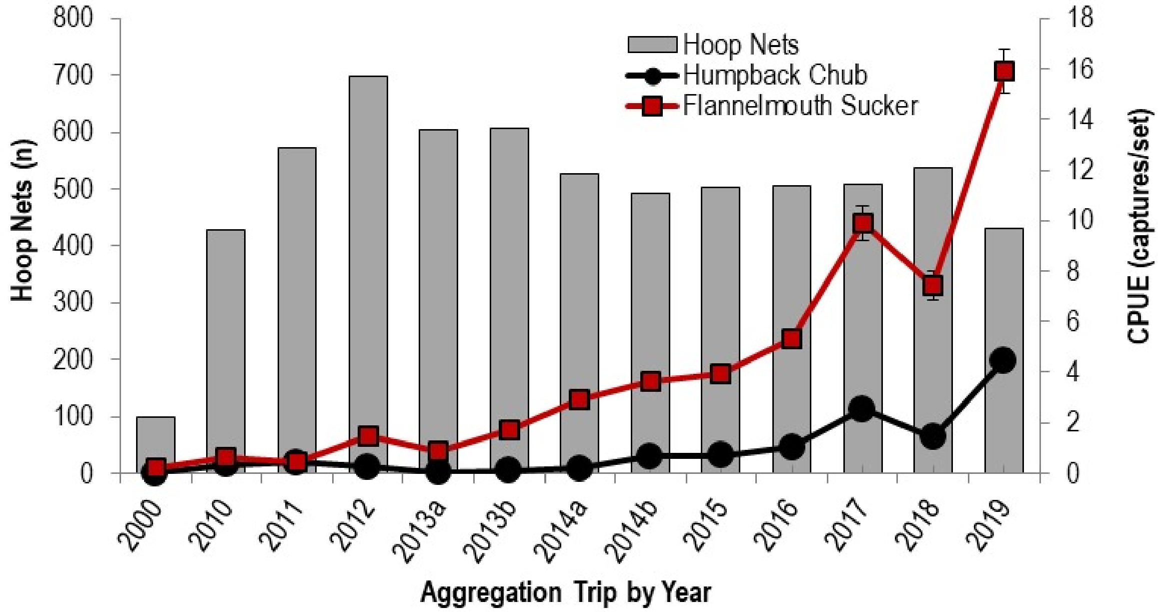


Figure 5. CPUEs of humpback chub *Gila cypha* and flannelmouth sucker *Catostomus lattipinnus* (all size classes) paired with total hoop nets set for each Grand Canyon aggregation trip 2000, and 2010-2019. Note in 2013 and 2014, two hoop netting aggregation trips [July (a), and September (b)] were conducted.

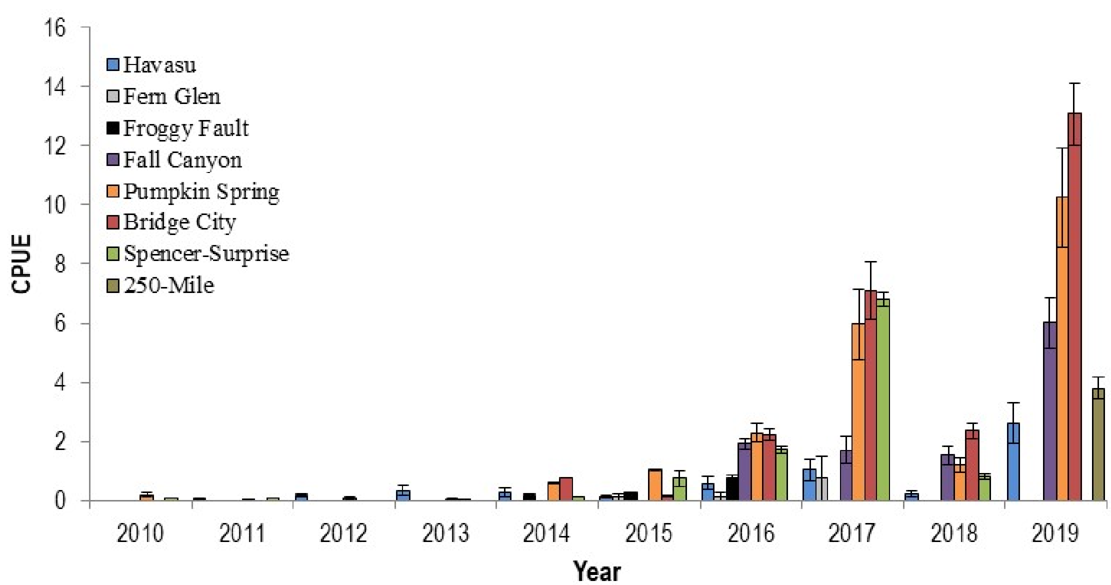


Figure 6. Mean CPUE ± 95% CI, captures per overnight hoop net) of adult humpback chub *Gila cypha* (≥200 mm TL) for sampling reaches from Havasu downriver 2010-2019. Approximate river miles for each site are as follows: Havasu (155.8-159.2), Fern Glen (168.5-172.5), Froggy Fault (196.0-198.5), Fall Canyon (210.2-213.9), Pumpkin Spring (212.5-216.0), Bridge City (236.6-238.7), Spencer-Surprise (245-249.5), and 250-mile (249.7-252.5). Note: The 250-mile reach was not sampled until 2019.

In addition, aggregation trips have been used to generate closed Chapman Petersen abundance estimates of humpback chub and flannelmouth sucker since 2017. In 2019, this included three discreet river reaches: 1) JCM-west, 2) Bridge City (RM: 236.6-238.7), and 3) 250-mile (RM: 249.7-252.5). We utilized data from the USGS 2019 fall JCM trip to function as a recapture event for the JCM-west reach and data from an additional USFWS 2019 Diamond Down trip to function as a recapture trip for sites below Diamond Creek. Humpback chub population (N) and density (fish/mile) estimates were possible at all three locations, but only at two locations for flannelmouth sucker. Estimated densities (fish/mile) of adult humpback chub (≥200 mm TL) in the JCM-west, Bridge City, and 250-mile reaches were 291 (95% CI: 204-378), 623 (95% CI: 519-727), and 158 (95% CI: 102-214), respectively. Flannelmouth sucker (≥200 mm) estimated densities in the JCM-west, and Bridge City reaches were 714 (95% CI: 604-825), and 290 (95% CI: 252-329), respectively.

During fall 2020, four river trips were conducted by the USFWS to monitor humpback chub in the mainstem Colorado River in Marble and Grand Canyons. The first two trips occurred during June and July 2020 to conduct a mark-recapture effort of HBC in the mainstem several miles upstream of Pearce Ferry between RM 273.9-275.9. These two 6-day trips were conducted as independent efforts by USFWS in lieu of the spring LCR monitoring trips, and to further understand the abundance of humpback chub in far western Grand Canyon, particularly where habitat is thought to be less than optimal. From these efforts, it was provisionally estimated there were ~200-300 adult humpback chub (TL ≥ 200 mm) per mile in this 2-mile reach of river. A third trip (our annual humpback chub aggregation trip) occurred from September 1-18, 2020 between Lees Ferry and Pearce Ferry. An objective of this trip was to continue a long-term relative abundance (catch per unit effort, or CPUE) index of humpback chub in the known historical aggregation sites. In addition, humpback chub were marked within four discrete river reaches as part of mark-recapture studies: 1) the JCM-west site near Pumpkin Spring (RM 210.2-213.8), 2) downstream of Diamond Creek between RM 227.2-229.2, 3) below Separation Canyon (RM 239.9-241.9), and 4) between RM 265-267. A final Diamond Down trip conducted during October 3-8, 2020 functioned as a recapture event for the three above mentioned sites where HBC were marked below Diamond Creek. All trips employed baited hoop nets as the gear type. Submersible antennas were also employed on marking event trips. 2020 data is undergoing analysis and will be provided at the Annual Reporting Meeting. Finally, USFWS is continuing to work toward estimating the total abundance of adult HBC in western Grand Canyon (Havasu Rapid to Pearce Ferry) via the application of capture probability to catch data.

G.6. Juvenile Humpback Chub Monitoring – West

The May 2020 JCM-west sampling did not occur due to COVID-19, but this reach was sampled in July and October 2020. Sampling occurred near Fall Canyon and consisted of three passes of hoop net captures and night-time electrofishing.

Additionally, submersible antennas were deployed. Methods for JCM-west were similar to those described for JCM-east (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 speckled dace (9274), flannelmouth sucker (7786), humpback chub (749), bluehead sucker (399), and unidentified suckers (2). Nonnative catch was comprised of rainbow trout (169), fathead minnow (105), green sunfish (50), brown trout (15), carp (8), and striped bass (1). While native species were more predominant in catch of the JCM-west site, catch of many nonnative species increased whereas catch of natives decreased relative to 2019 (note however, there were only two trips in 2020 compared to three trips in 2019). In the JCM-west reach, catch of humpback chub >79 mm TL was 408 in July and 179 in October. In addition, the number of humpback chub issued VIE marks between 40-79 mm TL was 66 in July and 38 in October.

Three different multistate population models were fit to PIT-tagged humpback chub mark-recapture data in Fall Canyon reach (Dzul and others, *in prep*). We present results from all three models to highlight some of the challenges of the Fall Canyon data and caution that more data is needed to obtain a better understanding of population dynamics and determine the best modeling approach for this system. Each model included five size states (80-99mm TL, 100-149mm TL, 150-199mm TL, 200-249mm TL, and >250mm TL) and included data from JCM-west (September 2017, May 2018, July 2018, October 2018, May 2019, July 2019, October 2019) and from humpback chub aggregations trips that visited Fall Canyon reach (August 2017, August 2018, August 2019). Abundance estimates are not presented for the first and last occasion (i.e., August 2017 and October 2019) because these are inestimable and non-identifiable, respectively. The first model only included mark-recapture data from physical captures (hoop nets and electrofishing). The other two models included antenna detections as well as physical captures but differed because one model assumed all fish were always present in the sampling reach (no temporary emigration) and the other model assumed that large subadults, small adults, and large adults could move in and out of the sampling reach (with temporary emigration). Abundance results differ between models (Figure 7). The model fit to only physical recaptures has the highest and most uncertain abundance estimates. This is likely because the number of physical recaptures of adults was very low, particularly prior to 2019. Abundance estimates are lowest for the model that allows for temporary emigration. The model that includes temporary emigration estimates that temporary emigration is relatively high across trips (19-35% of fish emigrated from the sampling reach each month), and because this model is the least restrictive of the three models, it is likely the best representation of true dynamics. One interesting finding is that the model with temporary emigration estimated a large increase in the number of unmarked adults in May 2019, suggesting perhaps that humpback chub may be more mobile when spawning in May.

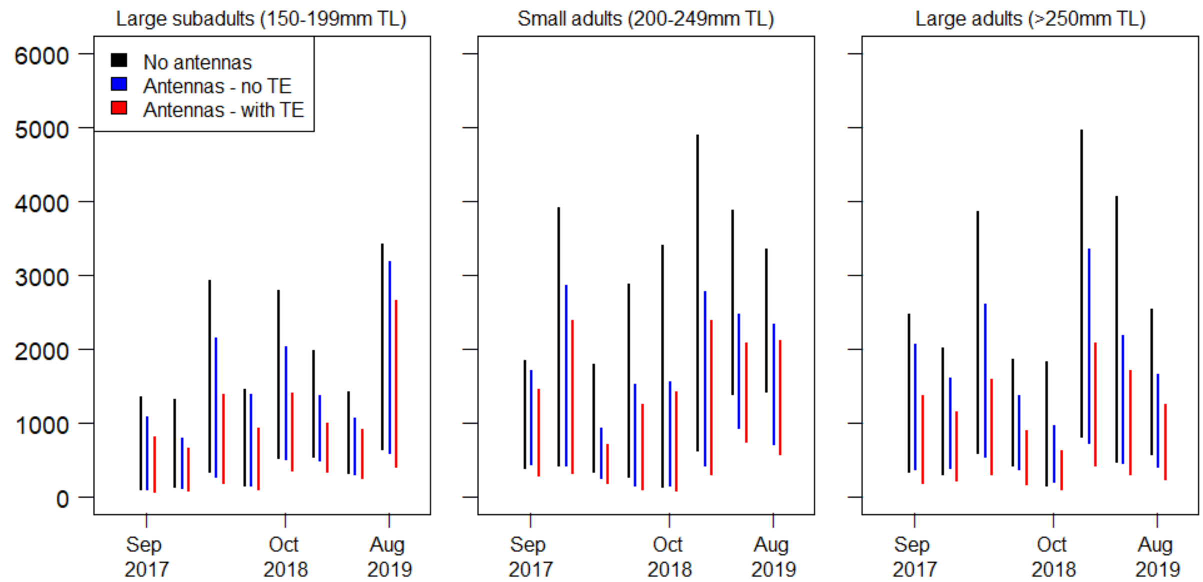


Figure 7. Abundance estimates for humpback chub *Gila cypha* subadults (150-199mm TL), small adults (200-249mm TL), and large adults (>250mm TL) in the Fall Canyon reach of western Grand Canyon. Estimates were obtained from three different models and 95% credible intervals are displayed for each occasion (Sep 2017, May 2018, July 2018, August 2018, October 2018, May 2019, July 2019, August 2019). The black lines show abundance estimates from the model fit to only physical captures (i.e., black lines- hoop nets and electrofishing), the blue lines show abundances from a model with both physical captures and antenna detections without temporary emigration (TE), the red lines show abundance from a model that included physical captures and antenna detections allowed for temporary emigration.

G.7. Chute Falls Translocations

The goals of this project, conducted by the USFWS, are to:

1) Annually translocate at least 300 juvenile humpback chub from lower portions of the LCR to upstream of rkm 14.2 (i.e., upstream of Chute Falls).

2) Annually monitor the abundance of humpback chub upstream of rkm 13.6 in the LCR. This includes monitoring in a small reach of river known as the “Atomizer reach” (rkm 13.6–14.1) and the reach of river known as the “Chute Falls reach” (rkm 14.1–17.7).

This project is identified as a Conservation Measure in the Biological Opinion. 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), destined to support a genetic refuge population at SNARRC, or for grow out and release into Shinumo, Havasu, or Bright Angel creeks. The project also fulfills a conservation measure to translocate HBC to upstream of rkm 13.6 in the LCR, intended to increase growth rates and survivorship, expand the range, and ultimately augment the LCR HBC population. In addition, this project provides managers with an annual index of abundance and trend of HBC residing upstream of rkm 13.6.

Translocations

Efforts to translocate humpback chub upstream of Chute Falls in the LCR have been ongoing since 2003. To date, approximately 4,142 juvenile (~80-130 mm TL) humpback chub have been translocated upstream of Chute Falls. Of these, 364 were released above Chute Falls (at rkm 16.2) on October 23, 2020. In June 2020, 415 humpback chub, collected in June 2019 and reared at SNARRC, were translocated into Bright Angel Creek by NPS biologists. No translocations were conducted in Havasu or Shinumo creeks during 2020.

Monitoring

USFWS conducts an annual monitoring trip upstream of rkm 13.6 in the LCR. The purpose of this effort is to annually monitor the abundance of humpback chub that are translocated upstream of Chute Falls, but also serves to monitor the abundance of humpback chub in the "Atomizer reach," the small section of river between rkm 13.6 and 14.1. This effort typically occurs in May or June, when river conditions are not flooding, and it is safe to conduct work activities in this stretch of river. Because of COVID-19 concerns during May, and a lack of flooding, we conducted this effort during October this year. Estimates are still forthcoming for October 2020, but Figure 8 shows estimates through 2019.

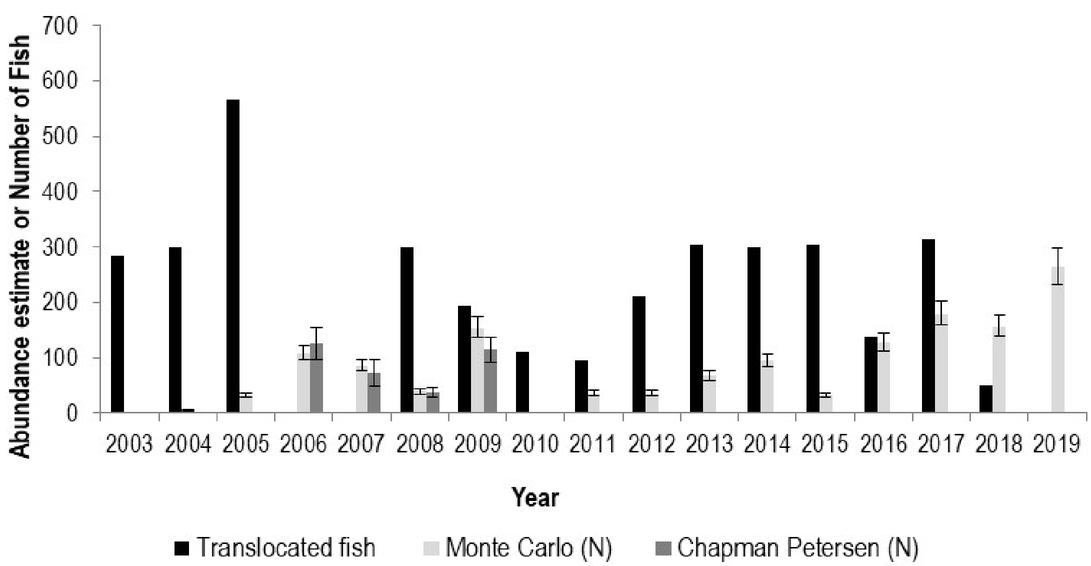


Figure 8. Numbers of juvenile humpback chub *Gila cypha* translocated to the Chute Falls (river km 14.1-17.7) reach since 2003 (black bars); and abundances of adult humpback chub ≥ 200 mm in the Chute Falls reach estimated with Chapman Petersen method (dark grey bars), and Monte Carlo simulation (light grey bars).

G.8. Havasupai Translocation Feasibility

This Project Element was not completed due to COVID-19.

G.9. Backwater Seining

The primary objective of this Project Element is to develop a long-term assessment of juvenile native and nonnative fishes in the Colorado River from Lees Ferry to Diamond Creek, including relative abundance metrics, species composition, size distribution, and the spatial distribution of backwater habitats. Seining represents a useful monitoring tool for assessment of both juvenile (particularly age-0) native and nonnative fish due to the high capture probability of the sampling gear and ability to easily sample across large spatial extents.

One backwater seining trip was conducted from September 14-27, 2020. A total of 2548 fish were captured during this sampling trip. Native fishes composed a majority of fish captured, which included 121 humpback chub (11-59 mm TL), 1716 flannelmouth sucker, 677 speckled dace, 11 unidentified sucker species, and 2 bluehead sucker. Nonnative fishes captured included 17 fathead minnow, 1 green sunfish, and 3 rainbow trout.

Science Questions Addressed & Results

Do rainbow trout have a negative effect on juvenile humpback chub? Yackulic and others (2018) estimated that juvenile chub (<100 mm TL) survival and growth during 2009-2016 declined when rainbow trout abundance was highest, but that temperature and turbidity are more important drivers than trout. Also, this model sheds light on our poor understanding of humpback chub recruitment — there is a lot of unexplained variability in the model that cannot be explained by rainbow trout abundance, density-dependence, temperature, or turbidity.

Are humpback chub in poor condition and spawning at a lower rate? There was an observed decline in adult humpback chub condition in 2014, but the relationship between condition and spawning rates remain an active area of research.

Has there been a massive decline in LCR-spawning adult humpback chub abundance? While USFWS spring LCR monitoring indicated a decrease in adult humpback chub in 2015 and 2016, this same dataset shows that adult abundance increased in 2017 and reached an all-time high in 2019 (Figure 3). Furthermore, the multistate population model fit to sampling efforts in both the mainstem and in the LCR did not find any evidence for a population decrease in 2015 (Figure 2). Lastly, the skipped migration model (Dzul and others, *in review*) suggests that including MUX detections leads to higher movement estimates in 2015-2016 compared to models fit without MUX detections, and indicates that humpback chub did move into the LCR in 2015 and 2016 but were not available for LCR USFWS sampling (i.e., fish likely moved in and out of the LCR before the start of the April monitoring trip). Altogether, there is strong evidence that there was no decline in adult abundance in 2015-2016.

Are Chute Falls translocation efforts adding a sufficient number of adults to the population to justify the costs? Yackulic and others (*in review*) estimate that Chute Falls translocations lead to an additional 246 (95% CI: 76-430) adult humpback chub in the LCR aggregation compared to not doing translocations. Also, in six of the eight years assessed (2009-2016), translocations had a beneficial effect on adult humpback chub abundance. This number accounts for downstream movement of translocated fish to the lower 13.56 km of the LCR as well as additional mortalities that result from translocations. Results indicate that translocations are beneficial and reduce the need for trout removals, but translocations are limited in their ability to produce large increases in adult abundance.

Do PIT tag antennas improve population models? Dzul and others (*in review*) compare models fit with and without antenna detections and show that including antennas leads to higher estimates of adult survival and higher estimates of adult movement from the mainstem to the LCR compared to models fit without antennas. These results suggest that a subset of the adult population is not as vulnerable to physical capture in hoop nets and that this can introduce bias in population models. Dzul and others (*in prep*) demonstrate that adding antenna detections to abundance estimation can improve precision.

Is juvenile humpback chub production decreasing in the LCR? Monitoring data suggests that 2011 and 2012 were years with very high age-0 production in the LCR, and that 2013-2015 were moderate production years, and that 2016-2018 were low production years. Most recently, 2019-2020 age-0 production looks to be high based on USFWS fall monitoring trips and the USGS LCR July trip. In the mainstem, JCM monitoring suggests a decrease in juvenile (<100 mm TL) humpback chub from 2012-2018 and large outmigration from the 2019-2020 cohort has not been observed.

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Budget

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$424,185	$2,000	$62,000	$520,666	$0	$82,960	**$1,091,811**
Actual Spent	$321,092	$3,947	$34,629	$955,273	$0	$78,271	**$1,393,212**
(Over)/Under Budget	**$103,093**	**($1,947)**	**$27,371**	**($434,607)**	**$0**	**$4,689**	**($301,401)**
FY19 Carryover	**$551,216**					**FY20 Carryover**	**$249,815**

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

- Lower costs in salary was due to needed field staff being provided by contractors instead of USGS employees. These costs are accounted for under the Logistics budget.
- Lower costs in operating expenses was due to the lack of a need to purchase planned for field equipment and supplies for trips cancelled due to COVID-19 closure of the Colorado River in Grand Canyon.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project H: Salmonid Research and Monitoring

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Summary

Protection of the endangered humpback chub *Gila cypha* near the Little Colorado River remains one of the highest priorities of the Glen Canyon Adaptive Management Program (GCDAMP). A concurrent priority of the GCDAMP is to maintain a high-quality rainbow trout sport fishery upstream from Lees Ferry in Glen Canyon. As such, rainbow trout *Oncorhynchus mykiss* were an important component in the development of the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) (U.S. Department of Interior, 2016a) and thus were a major consideration when developing Glen Canyon Dam (GCD) operations and experimental flows included in the selected alternative and LTEMP Record of Decision (ROD) (U.S. Department of Interior, 2016b).

Goals and Objectives

Experimental flows proposed in the LTEMP were designed to limit rainbow trout recruitment and dispersal out of Lees Ferry with a goal of maintaining the balance between the sport fishery and the downstream humpback chub population. However, ecosystems are dynamic and there has been a large increase in brown trout *Salmo trutta* recruitment upstream from Lees Ferry over the past few years. Given this new development, it is unclear whether the expansion of brown trout will disrupt the balance between rainbow trout and endangered native fishes downstream, and further, to what degree flow manipulations can be used to manage both species concurrently.

This project is composed of four integrated elements: the first three (H.1 - H.3) are research elements, and the last (H.4) is a monitoring element.

Science Questions Addressed and Results

H.1. Experimental Flow Assessment of Trout Recruitment

Project Element H.1, as described in FY 2018-20 Triennial Work Plan (TWP), is a new research project called Trout Recruitment and Growth Dynamics (TRGD). The data collection and analyses are intended to determine the effects of LTEMP ROD flows on the recruitment of young-of-year (YOY) rainbow trout and brown trout in Glen Canyon, the growth rate of juveniles and adults, and dispersal of YOY trout from Glen Canyon. The other goal that is central to this study is to increase our understanding of the key factors (trout density and recruitment, prey availability, nutrients, etc.) that control the abundance and growth of the Glen Canyon trout population. This improved understanding could lead to the identification of policies other than flow manipulation that could benefit the Lees Ferry fishery and limit the downstream dispersal of rainbow trout to the Little Colorado River, as well as controlling brown trout should this species become more prevalent in Glen Canyon.

Study Objectives:

The objectives of project H.1 are to evaluate:

1. The effects of higher and potentially more stable flows in spring and summer during equalization events on trout recruitment, growth, and dispersal.
2. The effect of fall High-Flow Experiments (HFEs) on recruitment of trout in Glen Canyon, measured either through direct effects on juvenile survival or through reduced egg deposition in later years driven by reduced growth of trout (which reduces fecundity and rates of sexual maturation).
3. The effect of spring HFEs on trout recruitment, growth, and dispersal.
4. The effect of Trout Management Flows (TMFs) on rainbow and brown trout recruitment and dispersal.

This sampling scheme was implemented in Glen Canyon where juvenile and adult trout (rainbow trout and brown trout) are sampled in two sub-reaches four times a year, and in a single sub-reach (-4 river mile, sub-reach 1C) five times a year. For purposes of study replication, three sub-reaches were established, and each assigned a 3-km length. Each sub-reach contains a combination of low-angle (spawning bars) and high-angle (talus slopes) shorelines; and in sum, these three sub-reaches represent 36% of the total shoreline length of Glen Canyon.

The primary objective of this Project Element is to assess the effectiveness of GCDAMP policy actions that influence abundance, survival, recruitment, and movement for two distinctly different trout species.

These types of information have management implications, particularly downstream from Glen Canyon Dam where trout dynamics are central to understanding how to manage a functional sport fishery at Lees Ferry and its downstream relationship to native fish conservation in Grand Canyon. Secondly, owing to management concerns regarding brown trout establishment and population expansion in Glen Canyon, efforts are being made to understand brown trout population dynamics. All fishery data are used for informing models used to estimate population dynamics of rainbow trout and brown trout. Currently, both trout species are marked with passive integrated transponder (PIT) tags and released unharmed to monitor movement, growth, and to determine variation in capture probabilities. This is done to improve our understanding of environmental factors (flows, nutrients, temperature, trout density, and size structure) that may influence these two distinctly different trout species in Glen Canyon. As previously reported, removal efforts of brown trout in sub-reach 1C as part of sampling by the Natal Origin and TRGD projects had limited researchers' ability to monitor this trout population (USGS, 2019). Resumption of tagging has increased the proportion of brown trout with PIT-tags, as well as secondary recaptures that are required to estimate abundance and vital rates such as growth, survival, and movement. This set of metrics will provide resource managers and the GCDAMP the means to make better informed inferences on the status and trends of this problematic species and determine the efficacy of the joint National Park Service and Arizona Game and Fish Department (AGFD) effort to incentivize anglers to harvest brown trout (AZGFD/NPS 2020). Both trout species are considered problematic to downstream fishery resources in Grand Canyon and may require different management actions (Yard and others, 2011; Korman and others, 2015; Korman and others, 2020).

General Overview

In FY 2020, a total of 30,166 fish (rainbow trout [29,865]; brown trout [3,506]; flannelmouth sucker [267]; green sunfish [25]; common carp [6], striped bass [2] and walleye [1]) were captured by electrofishing across four seasonal sampling trips (November, January, June, and September) conducted in Glen Canyon. Owing to safety concerns related to COVID-19, the April sampling trip was cancelled and rescheduled for June 2020.

The catch proportion for brown trout continues to be highest in the lowest sub-reach 1C (FY 2020 brown trout catch proportions are: 1A – 10%; 1B – 5%; and 1C – 24%; based on 1st electrofishing pass). As of fall 2020, the TRGD sampling design was modified (excluding sub-reach 1B) that will result in a 33% reduction in overall sampling effort. For this reason, catch data for brown trout from sub-reach 1-C will only be used to draw inferences on the status and trends of this problematic species from 2012-2020 (Figure 1).

Brown trout catch rates continue to show seasonal increases year over year. In FY 2020, the brown trout catch rates (fish/km) were the highest of all previous years (2012-2020) and across all size distributions recorded. Notably, the September 2020 brown trout catch for age-0 (< 124-mm fork length [FL]) fish was the largest observed indicating continued and increasing reproductive success. Owing to the broad size distributions for age-0 brown trout, there is likely a protracted spawning period for this species. Factors likely controlling the catchability of brown trout are fish size, fish density, spawning behavior, and elevated water temperatures, particularly in the late-summer and fall seasons (Korman and Yard, 2017a).

Currently, brown trout appear to be a self-sustaining and growing population, one that up to most recently has remained scarce and unexplained. Our observational data would suggest that brown trout are spawning between November-January, in contrast to rainbow trout that spawn later in the spring, typically March-April. The time intervals for development (pre- and post-hatch) are similar between the two species; therefore, we would expect to observe juvenile brown trout occurring in our electrofishing catch well before rainbow trout of equivalent size. Juvenile rainbow trout (< 75-mm FL) are observed in the electrofishing catch by June; however, brown trout appear to be invulnerable to capture until the September and November trips. By that time, juvenile brown trout are usually 15 to 20 mm longer than rainbow trout.

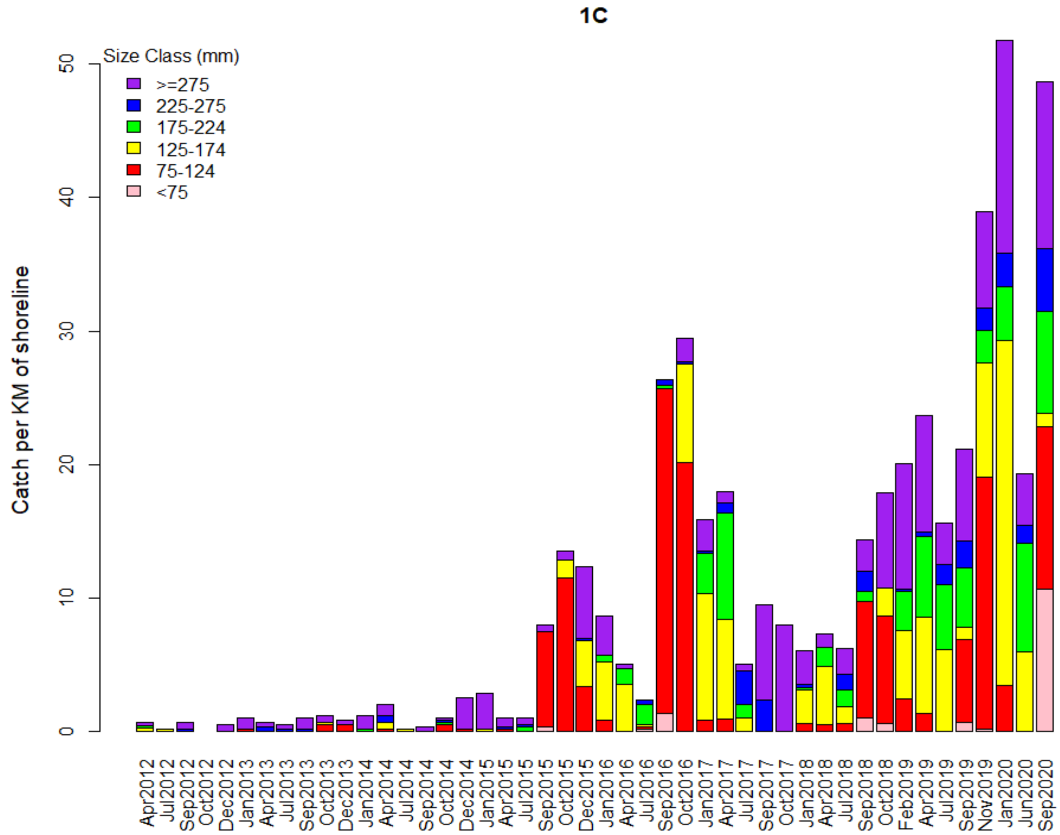

Figure 1. Brown trout catch rates in Trout Recruitment and Growth Dynamics reach 1C between 2012 and 2020 by 50 mm size class based on data from the first electrofishing pass.

One hypothesis that explains the catch difference between the two trout species is that brown trout are not occupying the near shoreline (wetted edge) like rainbow trout when smaller in size. An alternative hypothesis is that adult brown trout have a more protracted spawning period that begins earlier and partially overlaps with rainbow trout. This would result in a broad size-distribution for age-0 brown trout and owing to scarcity makes the modal size not as prevalent. Highest brown trout catch, and largest size classes, are currently found in the downstream sub-reach, 1C (Figure 2). Currently, we are unable to report on brown trout abundance until we update the brown trout model. Owing to increased capture probabilities for brown trout these abundance estimates are likely to be reported on in January 2021 during the Annual Reporting Meeting.

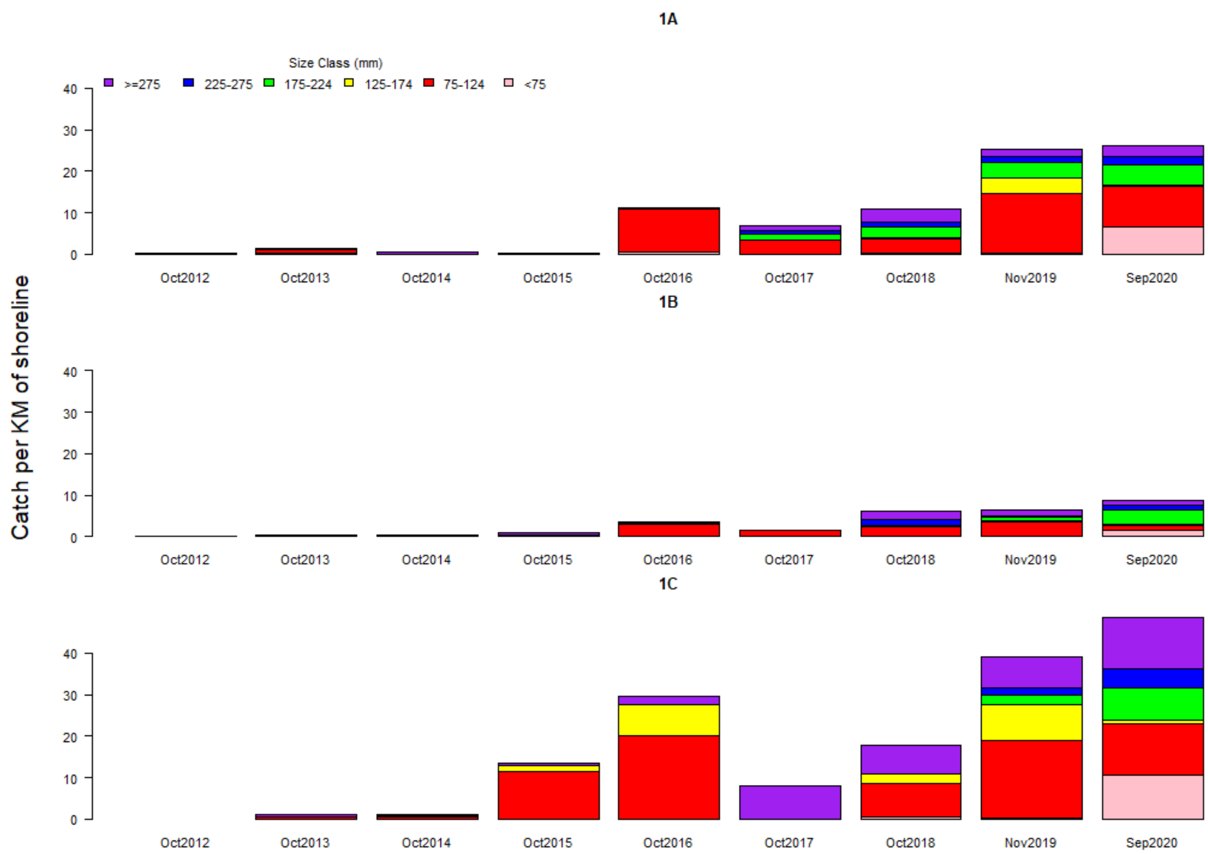

Figure 2. Brown trout catch rates by 50 mm size class in Trout Recruitment and Growth Dynamics sub-reaches 1A, 1B, and 1C during months when all three reaches were consistently sampled.

Relative condition factor for both rainbow trout and brown trout in Glen Canyon remains high (Figure 3). The increase in the winter-summer condition factor strongly suggests that growing conditions continue to be marginally good for large rainbow trout (≥ 275 mm FL). Notably, the April 2020 trip was cancelled due to COVID-19, therefore the relative condition for both species prior to the Bug Flow experiment (see Project F) in 2020 remains unknown.

Secondly, the declining trend in rainbow trout relative condition since 2016 appears to have stabilized and remains well above the average relative condition observed between 2012 and 2015. In contrast, the relative condition factor for brown trout, particularly large-sized fish, remains much higher than observed for similarly sized rainbow trout. There are three major points that need to be emphasized: 1) brown trout densities have increased over time (Figures 1 and 2) and these increases appear to be independent of the factors that led to the collapse of the rainbow trout population (i.e., reduction in invertebrate prey production due to a decline in nutrients) (Korman and others, 2017b; B. Deemer *pers. comm.*), 2) no corresponding change in relative condition factor was observed between brown trout and rainbow trout, essentially the factors regulating trout condition are not the same, and 3) large brown trout condition remains consistently higher than rainbow trout, even during the time period that invertebrate prey production likely declined. The sharp difference in condition factor observed between these two trout species suggests food resources are being partitioned differently by the larger sized fish. It is likely that brown trout are subsisting more on fish (rainbow trout) rather than just invertebrate prey items.

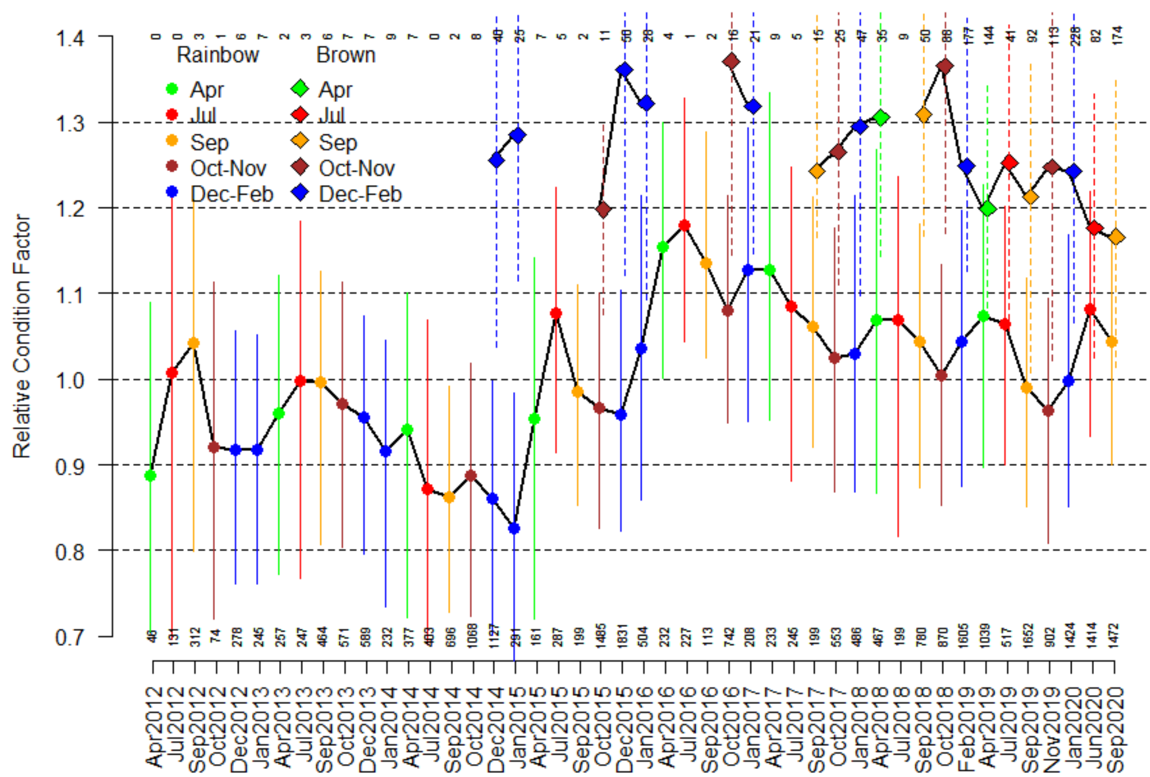

Figure 3. Relative condition factor for rainbow trout (circular symbol) and brown trout (diamond symbol) from electrofishing data collected in Glen Canyon, between April 2012 and September 2020 for fish with a fork length of 275 mm or greater. Points show the median value and error bars show the 80% credible interval. Seasonal sampling trips are symbolized by color: Green = spring (April), red = summer (June, July), orange = late-summer (September), brown = fall (October, November), blue = winter (December, January).

As originally proposed in the FY 2018-20 TWP, modifications were needed to update the existing Glen Canyon trout population model (Korman and others, 2017b). The modeling changes have been completed and we are able to report on some of the population dynamics of the rainbow trout population for the three sub-reaches. Results suggest that there is some spatial variability in the distribution of rainbow trout abundance (stratified by size-class) among the three sub-reaches: upstream (1A, Figure 4), middle (1B, Figure 5), and downstream (1C, Figure 6).

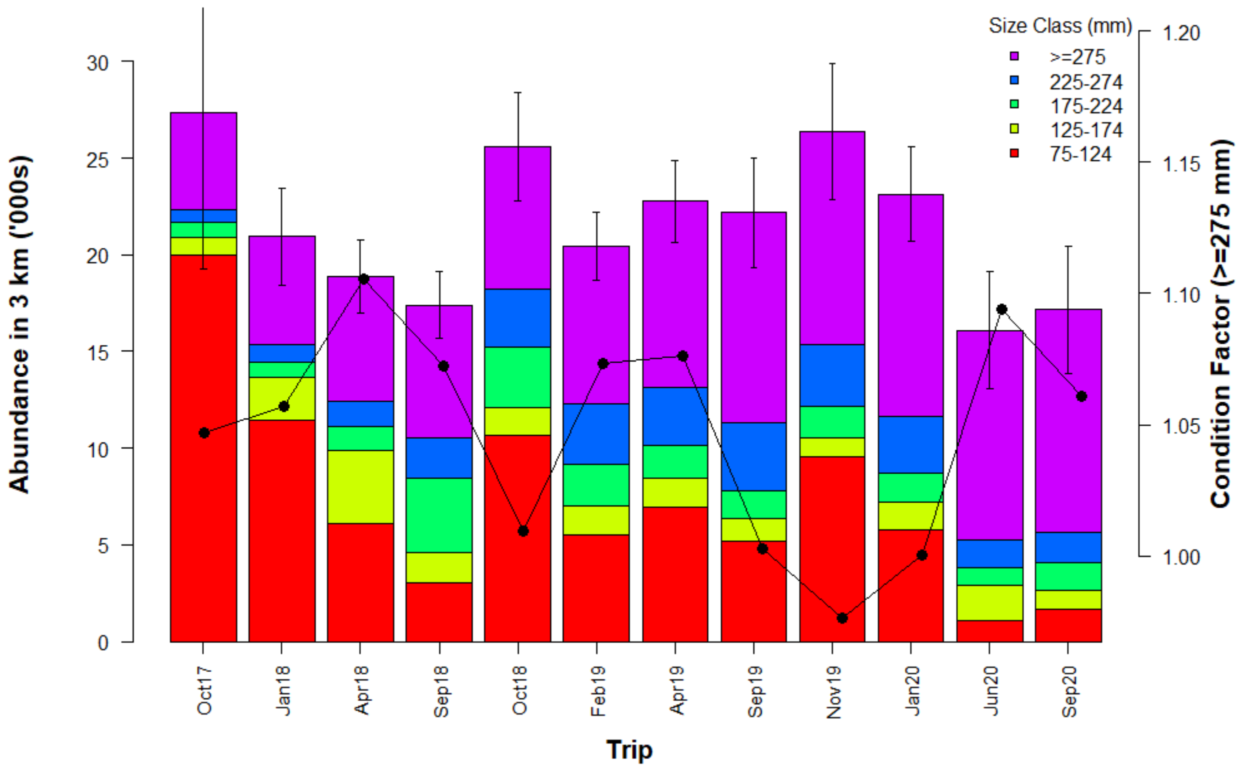

Figure 4. Rainbow trout abundance estimates (stratified by 5 size-classes) in the upper most sub-reach 1A during the Trout Recruitment and Growth Dynamics sampling period in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the relative condition of trout ≥ 275-mm FL in sub-reach 1A.

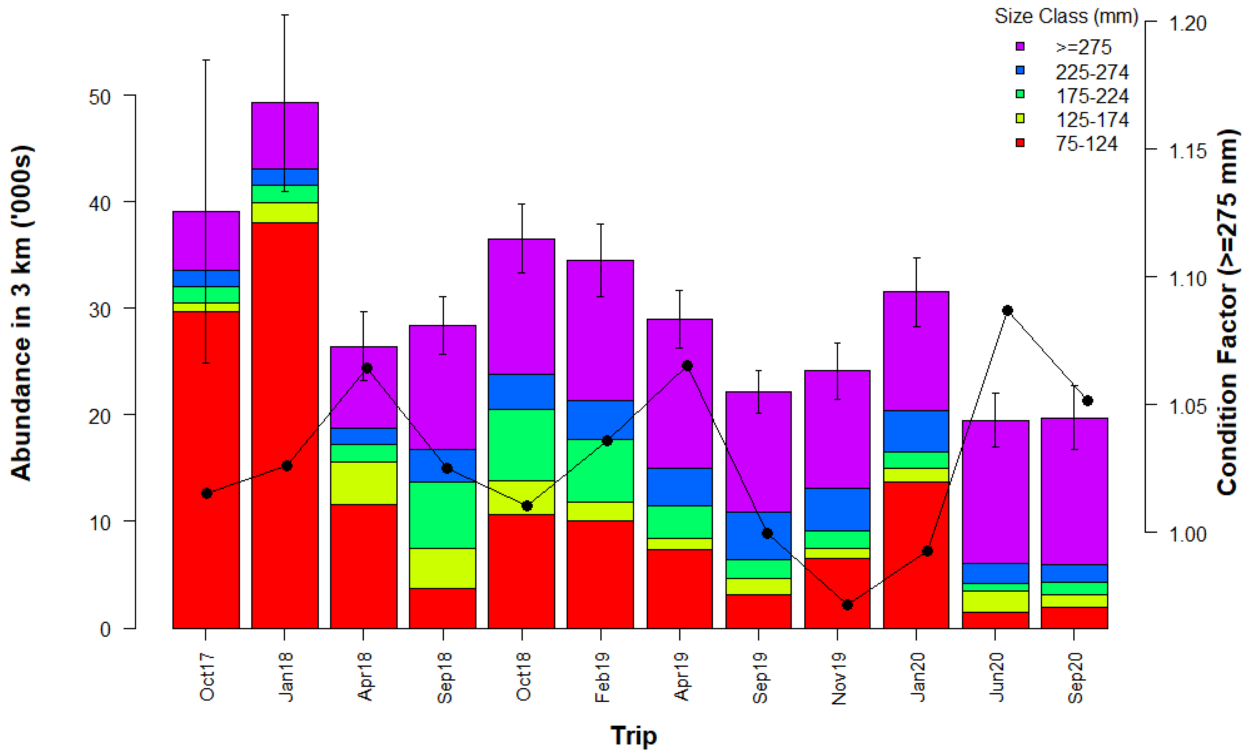

Figure 5. Rainbow trout abundance estimates (stratified by 5 size-classes) in the middle sub-reach 1B during the Trout Recruitment and Growth Dynamics sampling period in Glen Canyon, AZ. (Note that this sub-reach will be eliminated from the future sampling design as per FY 2021-23 TWP.) Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the relative condition of trout ≥ 275-mm FL in sub-reach 1B.

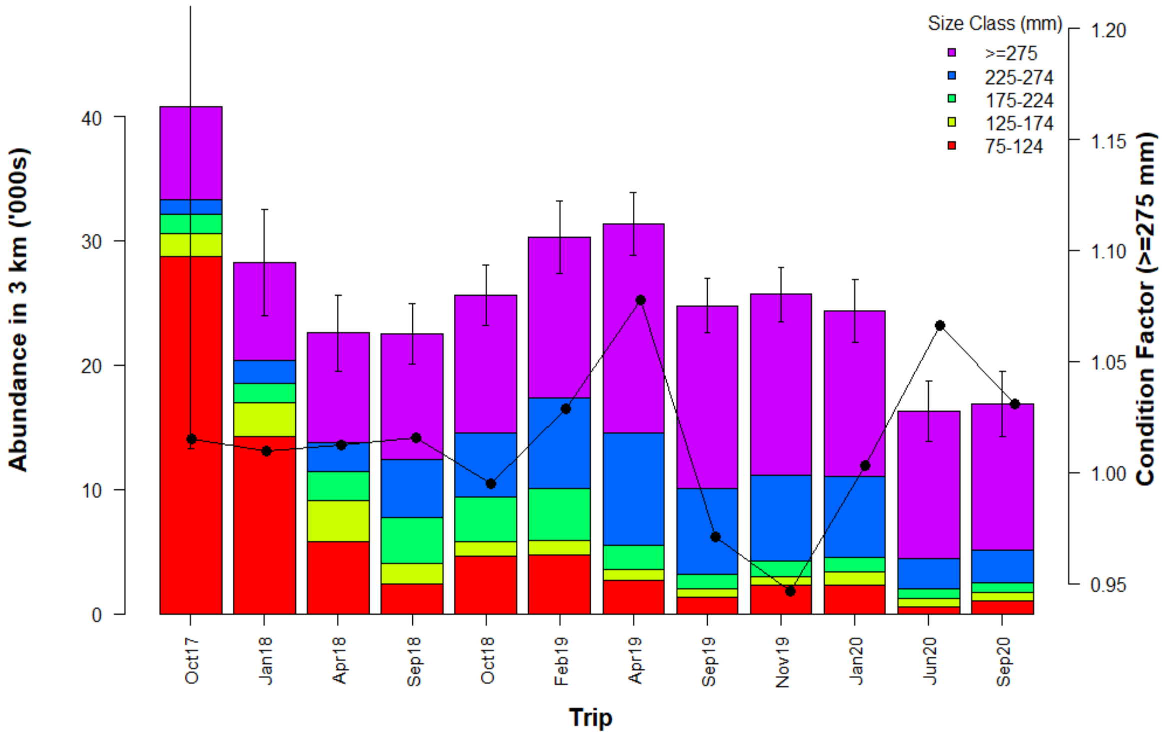

Figure 6. Rainbow trout abundance estimates (stratified by 5 size-classes) in the lowest sub-reach 1C during the Trout Recruitment and Growth Dynamics sampling period in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the relative condition of trout ≥ 275-mm FL in sub-reach 1C.

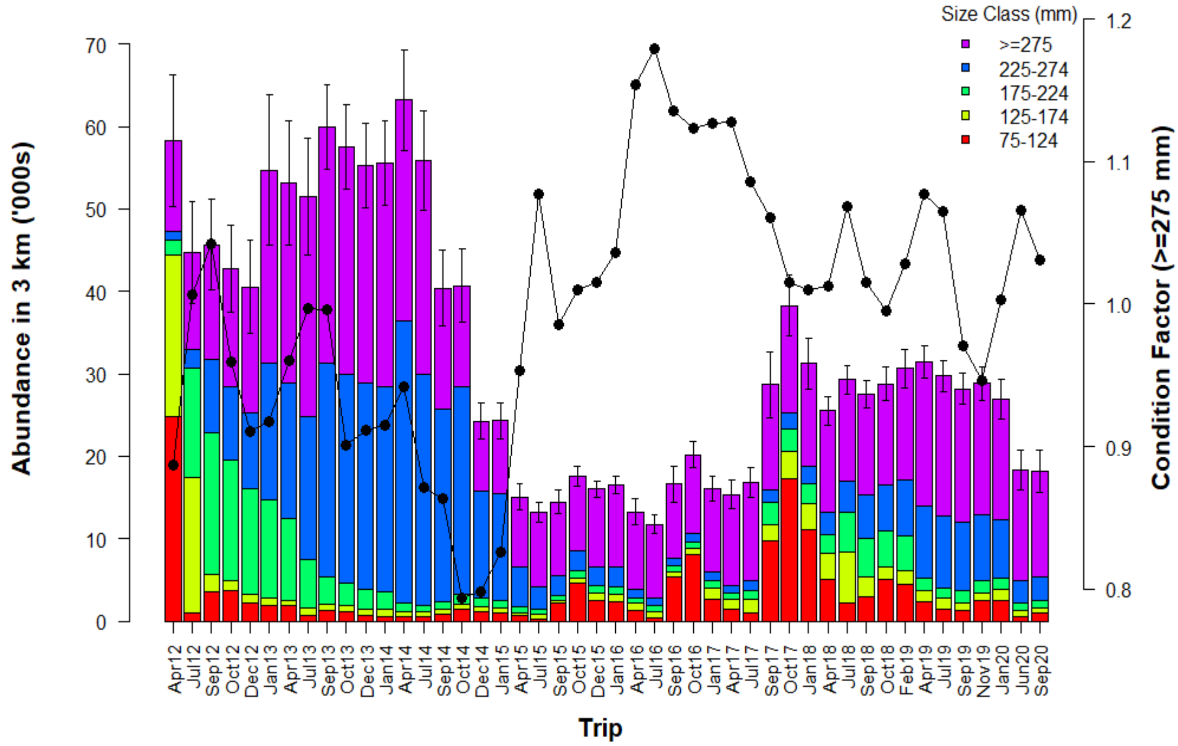

Figure 7. Rainbow trout abundance estimates (stratified by 5 size-classes) in the lowest sub-reach 1C for 2012-20 in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the percentage of marked to unmarked fish in the local population in sub-reach 1C.

H.1.1. Weekend Stable Flows (Bug Flows) in Spring and Summer

The analytical approach we intend to use will require additional years of data collected with and without flow treatments to determine how trout (rainbow trout and brown trout) dynamics in Lees Ferry respond to Bug Flows, which are weekend stable flows designed to improve aquatic insect egg survival during spring and summer. Currently, contrasts made between years with and without Bug Flows for late-spring and summer rainbow trout growth demonstrate no structural difference in growth or trout recruitment for the population (Figures 7 and 8).

H.1.2. Fall High-Flow Experiments

To date, five fall HFEs have been conducted between 2012 and 2020 (Figures 7 and 8). If there is an effect on trout related to HFEs, we hypothesize that the likely mechanism acts directly on the benthic invertebrate community and secondarily, on trout, by reducing the invertebrate prey available following the flow disturbance. Contrasts made between flow events (with and without HFEs) is a necessary requirement to determine if an effect exists; unfortunately, there are only three years over this time-period without HFEs (2015, 2017, 2019 and 2020).

Poor fall-winter growth was observed in three consecutive HFE years (2012-2014) across all catchable sized fish. These three consecutive HFE years were also accompanied by declining trout growth that was associated with the ultimate collapse in the rainbow trout population (late-2014). This trout population collapse could be independent of an HFE effect. Note that there was a progressive annual drop in soluble reactive phosphorus (SRP; B. Deemer *pers. comm.*) over the first three consecutive HFEs that is strongly correlated with trout decline that may explain trout population declines. The effect of HFEs versus SRP on reduced trout abundance, recruitment, and growth cannot currently be determined.

Poor growth in September-October 2012 occurred before the first fall HFE was implemented, suggesting that other factors (low SRP or high trout density, refer to Figure 2) might be depressing growth over the fall-winter period (similar conditions were repeated in 2013 and 2014). In fall of 2014, the occurrence of high trout growth before the HFE and low growth immediately after the HFE in the winter of 2015 does suggest a potential HFE effect in that year. However, the current population biomass has continued to decline irrespective of flow events. Since the trout population collapse, we compared seasonal growth differences in years with and without HFEs, based on weight change between pre- and post-flood periods and weight change between years, and reported that there might have been an HFE effect on monthly growth rates of rainbow trout (≥ 200 mm FL). The two years with HFEs (2016 and 2018) show only slight reductions in fall growth for rainbow trout within the HFE interval. In contrast, years without an HFE as observed in 2017, 2019, and 2020 all show small reductions in rainbow trout growth. The decline in rainbow trout growth in early fall (September-October) prior to an HFE might suggest that that this trout growth response is independent of the HFE. Note though, that growth was positive in the later fall (November-January) and winter intervals. We cannot report on April 2020 because of trip cancellation due to COVID-19.

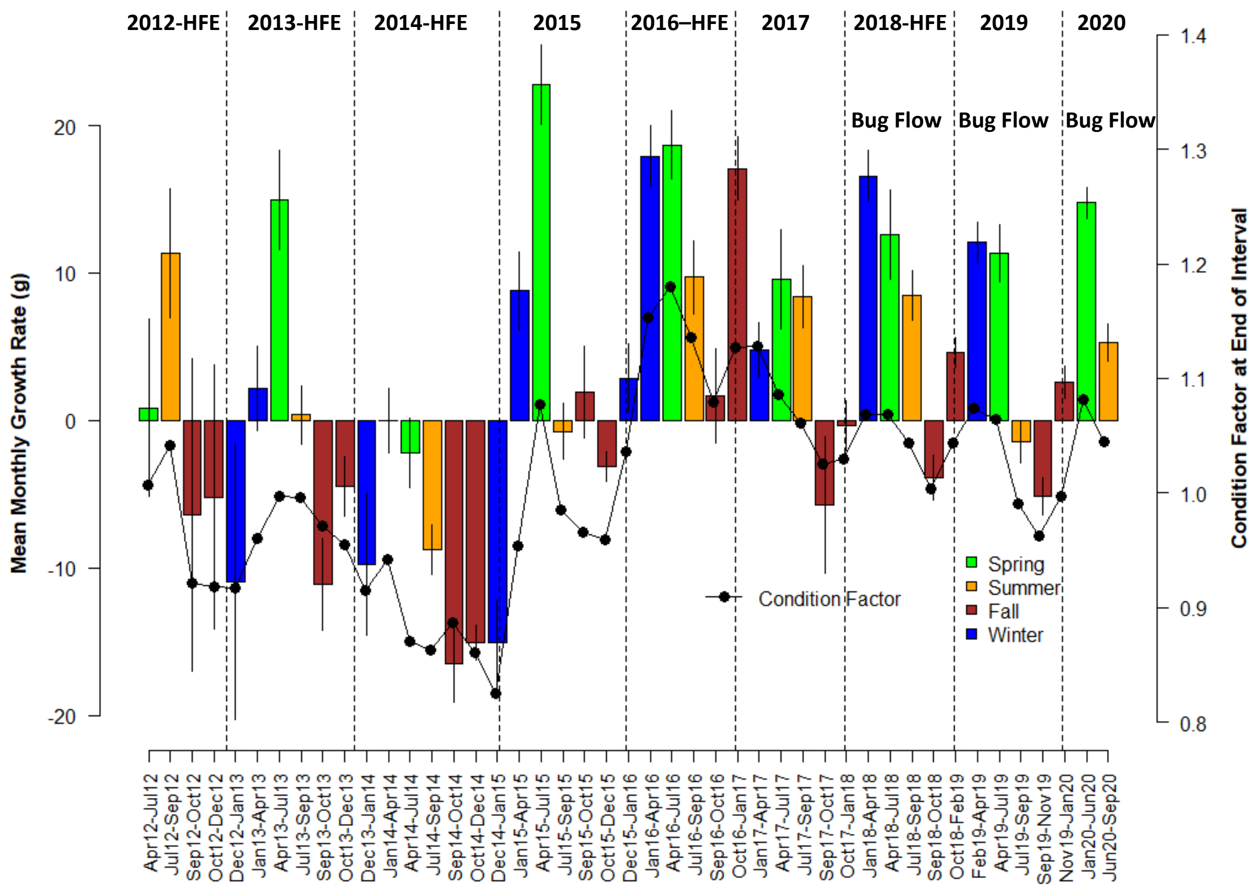

Figure 8. Mean monthly growth rate (g/month) estimates of a 300 mm fork length rainbow trout in Glen Canyon between April 2012 and September 2020. Monthly growth rates are each estimated for each interval between sampling trips with colors representing seasons: Spring = green; Summer =orange, Fall = brown, and Winter = blue.

H.1.3. Spring High-Flow Experiments

No spring HFEs were implemented during our monitoring period (2012-20).

H.1.4. Trout Management Flows

Trout Management Flows are intended to reduce the probability of large recruitment events of young rainbow trout in Glen Canyon. At present, a literature review on fish stranding in natural and regulated river systems is being developed. This synthesis is focused on differences in stranding between fish species and size, as well as the stranding relationships found between shoreline slope, substrate, discharge, and other physical attributes.

Results from a hypsometric analysis of Glen Canyon that quantifies the stage-discharge relationships for area of inundation, slope, substrate types, and flow velocity distributions will be part of this review. The flow stranding report is expected to be completed by May 2021.

H.2. Rainbow and Brown Trout Recruitment and Outmigration Model

Although originally focused on rainbow trout recruitment and outmigration models, the focus of this Element was almost immediately shifted to the development of the brown trout model for the 2017 Brown Trout Workshop and report (Runge and others, 2018) and further modifications and updates since then as the availability of mark-recapture data has increased and managers have requested annual updates. The model uses both mark-recapture and catch per unit effort (CPUE) data to estimate brown trout recruitment, growth and survival. This model served as the basis for comparing evidence for various hypothesized drivers of recent increases in brown trout. We then coupled this model with previously developed models of rainbow trout and humpback chub population dynamics to simulate the potential impacts of different management scenarios. In FY 2019 and FY 2020, as mark-recapture data became richer, we were able to relax assumptions in the original model. Given the sparsity of brown trout mark-recapture data, output have been sensitive to assumptions in the form of priors before collection of the 2019 data (Figure 9). Prior is a term commonly used in Bayesian statistics, where a prior is defined as the probability distribution of an uncertain quantity/parameter before empirical data is accounted for in the model.

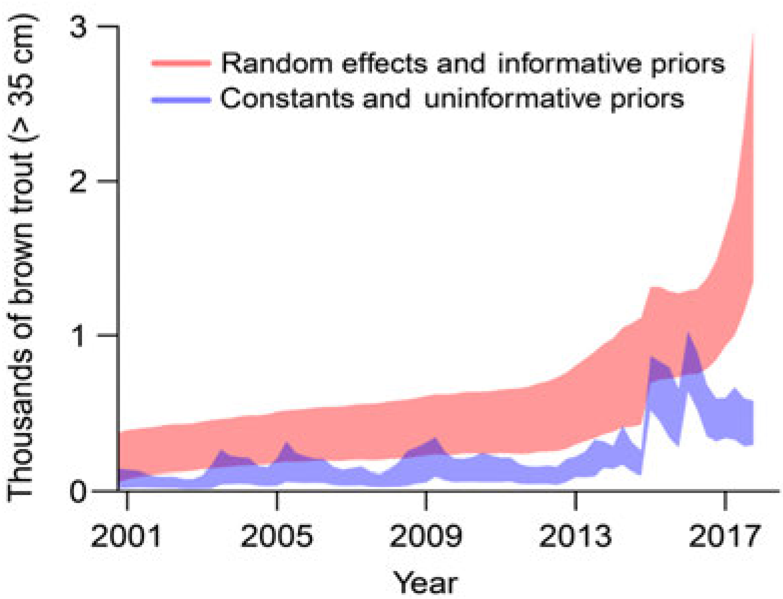

Figure 9. Estimates of brown trout over 35 cm (~14 in) over time in the Glen Canyon reach of the Colorado River under a model that includes random effects and informative priors or a model that assumes constant rates and uninformative priors. Constant models without informative priors suggest a volatile population, but also lead to estimates of other parameters that are unlikely. Inclusion of random effects and informative priors lead to parameter estimates closer to previously published estimates. (Recreated from Figure 3 in Yackulic and others, 2020)

H.3. Using Early Life History and Physiological Growth Data from Otoliths to Inform Management of Rainbow Trout and Brown Trout Populations in Glen Canyon

The objective of this Project Element is to use life history and growth information contained within rainbow and brown trout otoliths to inform the management of trout populations in Glen Canyon. Sub-elements for this work included: 1) collecting a limited number of age-0 rainbow trout to obtain early life history data to continue to inform existing rainbow trout recruitment models, 2) collecting age-0 brown trout to determine hatch and emergence dates to inform the timing of future experimental floods, and 3) collecting age-0 brown trout after experimental floods (e.g., TMFs, HFEs) to determine their immediate growth response to flow perturbations relative to brown trout survival. As mentioned in Project Element H.1, a TMF was not implemented in the FY 2018-20 work plan; therefore, we could not collect brown trout to examine growth responses to this type of experimental flow. Due to insufficient sediment inputs, HFEs were not implemented in fall 2017 (FY 2018) nor fall 2019 (FY 2020). While an HFE was conducted in fall 2018 (FY 2019), the fall TRGD and AGFD trips sampled fish in Glen Canyon prior to the HFE, so we could not collect brown trout samples post-HFE to determine short-term growth responses to this type of experimental flow. A spring HFE did not occur in FY 2020.

From FY 2018-20, we obtained age-0 brown trout samples in conjunction with sampling conducted on TRGD trips, with the end goal of estimating hatch and emergence dates via back-calculation for brown trout in the Glen Canyon reach. The original sample design included piggybacking on trips that were already going out to save on costs, as this Project Element did not include a budget for logistical costs. However, we underestimated how difficult it would be to capture age-0 brown trout in spring and early summer during their earliest life history stage. While approximately 35 age-0 samples were collected from FY 2018-19, many of the samples were larger-bodied from the fall TRGD trips, and it becomes more difficult to accurately count daily growth rings.

As mentioned in Project Element H.1, brown trout spawn over a three-month period (November-January) in advance of rainbow trout (March-April), so the early life history stages of age-0 brown trout should precede those of rainbow trout. Although a spawning offset exists between the two species, age-0 rainbow trout are detected along the shoreline during the June-July sampling effort. However, few if any young brown trout are detected prior to or during the same TRGD sampling effort as would be expected based on their earlier spawning time. Instead, juvenile brown trout are readily caught in September and October at sizes much larger than are observed for young rainbow trout. Such differences in size-at-capture between species suggests that age-0 brown trout are not occupying the near shoreline (wetted edge) when smaller in size, as rainbow trout do. Since conventional sampling methods were unable to capture larval and early life stage brown trout in spring and summer, a different approach is needed to find fish and complete the work initially proposed in this work plan.

In FY 2021 we will be conducting a targeted sampling of age-0 brown trout in Glen Canyon that is similar in study design to the Rainbow Trout Early Life Stage Survey (RTELSS) effort, which took place intermittently between 2003-15. This effort, the Brown Trout Early Life Stage Survey (BTELSS), includes a logistical operations budget to launch multiple targeted trips in spring 2021. BTELSS sampling will be conducted monthly (January-May) to determine brown trout hatch date distribution, hatch success and early survival, daily incremental growth, and relative densities across the late winter and spring months (Campana, 1992; Korman and Campana, 2009; Stevenson and Campana, 1992). The BTELSS study design will resemble that from previous RTELSS work, with at least 20 sites sampled per trip via a combination of backpack and boat electrofishing, with sites equally distributed between low and high angle nearshore habitat types. It is our hope that this intensive sampling effort throughout Glen Canyon will yield more age-0 brown trout in the spring timeframe that will facilitate examination of otolith microstructure.

H.4. Rainbow Trout Monitoring in Glen Canyon

The cold tailwater downstream of Glen Canyon Dam is an important rainbow trout recreational fishery. The goal of monitoring in Glen Canyon is to monitor 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. AGFD used three approaches to monitor the Lees Ferry fishery: 1) boat electrofishing, 2) angler surveys (creel) including the use of a game camera, and 3) a pilot citizen science program with angling guides to measure fish caught by their clients.

Boat electrofishing is used to obtain a representative sample of the fish community within this reach. The general objectives are to monitor the trout fishery and gather long-term trend data on relative abundance using CPUE methods, population structure (size composition), distribution, growth rate, relative condition and overall recruitment to reproductive size. These data are useful in monitoring overall trends in the trout population but may not allow assessments of short-term responses to specific dam operations. In addition, we conducted one night of nonnative sampling trip within this reach to detect warm water nonnative species during summer and autumn sampling trips (Project Element I.2).

To monitor the status of the Lees Ferry fishery and estimate angler use, AGFD conducted angler surveys to obtain a representative sample of the recreational angling community at Lees Ferry. AGFD uses a stratified random sampling approach to select a subset of days for interviews of both boat and shoreline anglers. 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 pilot citizen science program is an attempt to quantify the exact size of the fish captured by anglers. This is a metric that was included in the Lees Ferry fisheries management plan but cannot be determined from angler surveys.

Summary of Progress

AGFD completed three monitoring trips in 2020, sampling 120 sites and capturing 2,599 fish (excluding the nonnative sampling). Rare nonnatives captured during normal monitoring were two common carp and 409 brown trout. We conducted angler interviews on 60 days (as of the end of October), and have data from 32 unique trips from the citizen science project. The monitoring activities funded include: one spring electrofishing trip (March 10-12, 2020, 40 sample sites), one summer electrofishing trip (July 15-19, 2020, 40 sample sites, plus an additional 16 sites for nonnatives, including a three pass depletion of the slough), one autumn electrofishing trip (September 21-25, 2020, 40 sample sites, plus an additional seven sites for nonnatives), angler surveys—six days each month (four weekend days, and two weekdays), and the citizen science project (two guides and two private anglers participating).

H.4.1. Electrofishing

Rainbow trout continue to dominate the fish community within the Lees Ferry reach, comprising 83.3% of the catch (standard electrofishing), with brown trout comprising 15.7% of the catch. This is a dramatic increase in relative abundance of brown trout compared to all previous years (Figure 10). Rainbow trout have maintained a self-sustaining population since the mid-1990s. Relative abundance, as measured by electrofishing CPUE, has fluctuated greatly since AGFD began standardized sampling in 1991 (Figure 11). Rainbow trout CPUE was the highest ever recorded in 2011–2012 but declined from 2012 to 2016. Rainbow trout CPUE in 2020 was lower than that observed in 2018 (1.92 vs. 2.65 fish/minute). Within the last three years, relative abundance of smaller rainbow trout (< 305 mm FL) has declined, but abundance of larger rainbow trout (> 306 mm FL) has remained steady (Figure 11). In fall, young of year accounted for 38% of the rainbow trout catch (compared to 49% in 2019), with a CPUE of 0.55 fish/hour (lower than 2019 at 1.36 fish/minute). After two consecutive years (2017-18) with high young of year abundance, a lower CPUE is a positive indicator for this rainbow trout population, as too many juvenile fish can lead to too much fish biomass in the system for the available food base.

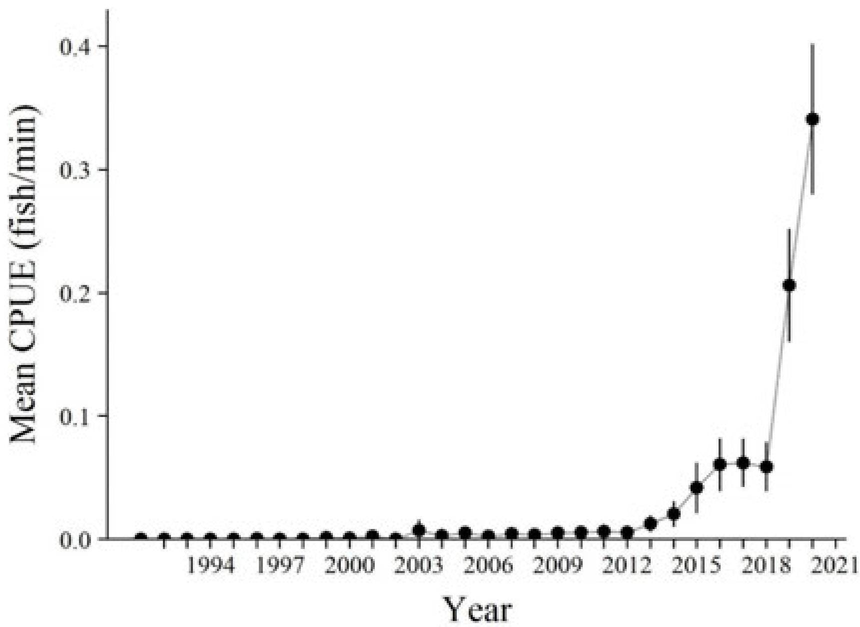

Figure 10. Mean catch per unit effort (fish/minute) of brown trout captured during Arizona Game and Fish Department's monitoring at Lees Ferry by year.

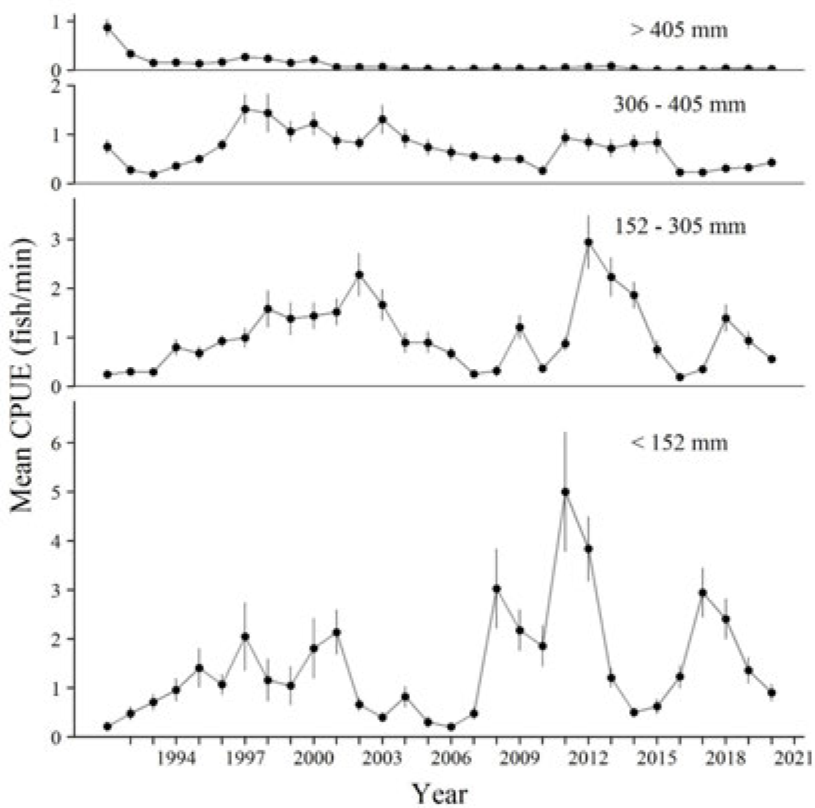

Figure 11. Average catch per unit effort (fish/minute) of rainbow trout at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing) by size class and year.

Relative fish condition for rainbow trout reached a record low (~0.8) in fall of 2014 and has been increasing since then. Condition of rainbow trout in 2020 was good with the mean condition above 0.95 for all size classes across all sampling trips. During our summer monitoring it was greater than 1.0 for the 306-405 mm Total Length (TL) size class, and just under 1.0 (0.98) for the 152-305 mm TL size class.

H.4.2. Angler Surveys (Creel)

For angling surveys, we use a calendar year for summarizing data on angler use, CPUE, and other metrics. At the time of this report (December 2020) we were still collecting angling data and results based on data from January through October (60 creel days, 854 boat anglers, 251 walk-in anglers). Boat angler CPUE and 95% confidence intervals for rainbow trout from January through October was 0.67 fish/hr [0.60, 0.74], while for walk-in anglers it was 0.21 fish/hr [0.16, 0.27]. CPUE in 2020 was lower than in 2019, and lower than the AGFD's goal for the fishery of 1.0 fish/hr. We saw a decrease in angler-reported captures of brown trout. Up to the end of October 2020, only 24 brown trout were reported captured during angler surveys, while over the same January-October period in 2019 anglers captured 87 (Figure 12).

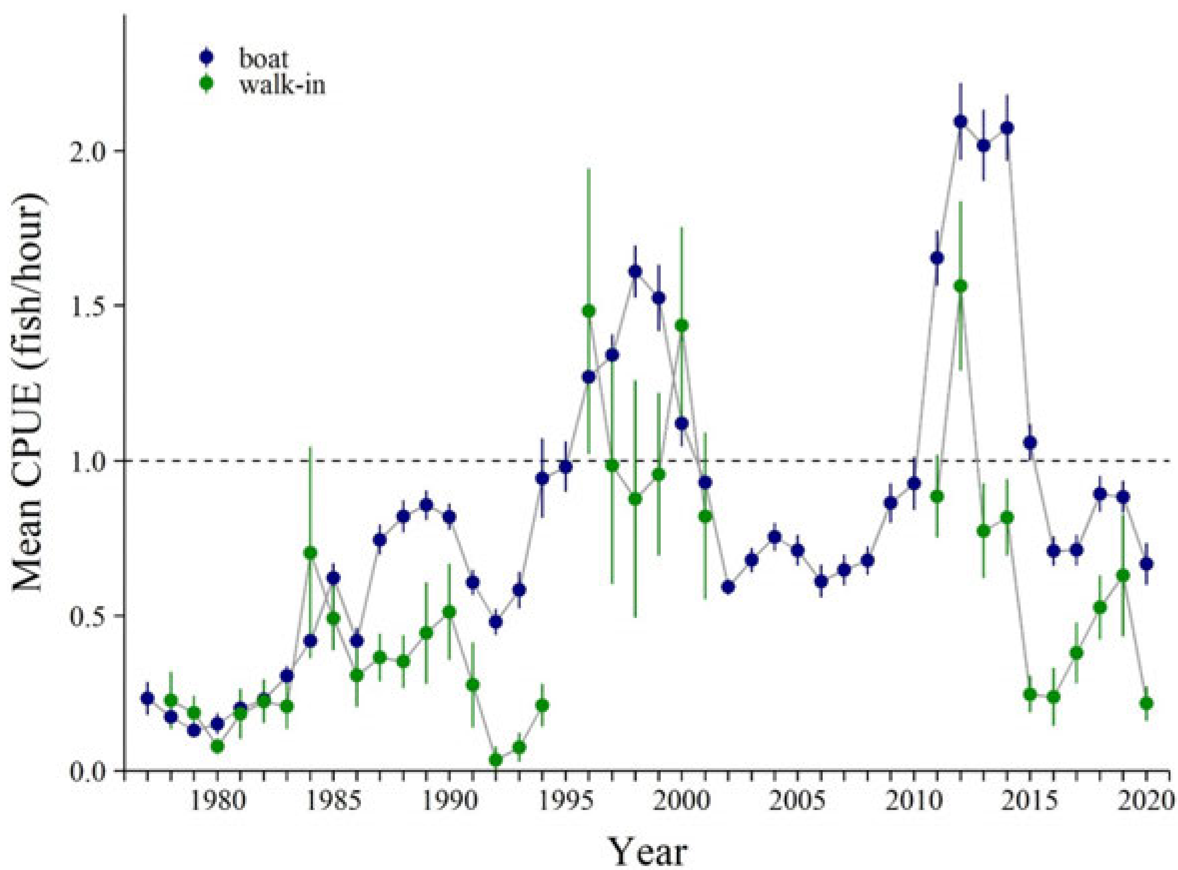

Figure 12. Angler per unit effort (CPUE, fish/hour) at Lees Ferry as determined from AGFD angler survey data. The dotted line at 1.0 fish/hour represents the management goal for the fishery.

H.4.3. Citizen Science Program

In 2020, two guides and two private anglers provided data for the citizen science program. We are still working on data entry and will have results ready to provide at the Annual Reporting Meeting in January 2021.

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Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden	Total
						13.794%	
Budgeted Amount	$272,040	$7,236	$25,160	$148,000	$0	$46,434	**$498,870**
Actual Spent	$170,405	$2,068	$67,592	$246,000	$0	$40,495	**$526,560**
(Over)/Under Budget	**$101,635**	**$5,168**	**($42,432)**	**($98,000)**	**$0**	**$5,939**	**($27,690)**
FY19 Carryover	**$134,637**					**FY20 Carryover**	**$106,947**

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

- Lower costs in salary was due to needed field staff being provided by contractors instead of USGS employees and part of the salary of a vacancy. These contractor costs are accounted for under the Logistics budget.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs of operating expenses was due to the need to shift a cooperative agreement to a service contract which falls in this budgeting category.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

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

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Summary

The primary goal of the system wide monitoring program is to monitor the status and trends of native and nonnative fishes in the Colorado River from Lees Ferry, AZ to Lake Mead. Arizona Game and Fish Department (AGFD) 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.

Goals and Objectives

Species composition and relative abundance using catch per unit effort (CPUE) methods can be used to interpret trends in abundance and distribution of native and nonnative fish throughout Grand Canyon.

Science Questions Addressed & Results

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

AGFD completed two mainstem sampling trips in 2020. Due to COVID-19 restrictions and Grand Canyon National Park temporarily closing, a planned spring trip was canceled and the other delayed until summer. On the summer trip (June 21 – July 6), 2,630 fish were captured at 249 electrofishing sites; 2,021 fish captured in 113 baited hoop nets and 34 fish were captured angling (13 humpback chub *Gila cypha*). During the fall sampling trip (Oct 25-29) from Diamond Creek to Pearce Ferry Rapid, 823 fish were captured at 84 electrofishing sites, 922 fish were captured in 62 hoop net sets, and two fish (both humpback chub) caught by angling on four nights. Most fish captured were flannelmouth sucker (*Catostomus latipinnis*; Table 1; 65% of electrofishing catch, 79% of hoop net catch). AGFD captured 298 humpback chub in baited hoop nets set from Lees Ferry to Pearce Ferry Rapid (RMI 280.8; 15% of hoop net catch). Since monitoring began in 2000, relative abundance of most nonnative species has decreased, and relative abundance of native species has increased (Rogowski and others, 2018).

Sampling in 2020 occurred in June and July which was outside the general time frame of previous years, so direct comparisons should be viewed with caution.

Table 1. 2020 Catch summaries for Arizona Game and Fish Department mainstem monitoring (electrofishing and hoop nets)

Native Species		Nonnative Species	
Flannelmouth Sucker	3327	Rainbow Trout	613
Speckled Dace	190	Fathead Minnow	6
Humpback Chub	320	Brown Trout	32
Bluehead Sucker	142	Common Carp	15
		Striped Bass	1
Native Hybrids		Green Sunfish	1
Flannelmouth/Razorback	4		
Total	3,983	**Total**	668

Asian fish tapeworm monitoring is conducted annually in conjunction with US Fish and Wildlife Service (USFWS) spring fish monitoring efforts in the Little Colorado River. A sample of humpback chub of various sizes (30-50 mm total length) are held in a collapsible tank on the riverbank and treated with Praziquantel at 6 mg/l for 48-hrs to cause tapeworms to be shed before fish are released alive (Ward 2007). In 2020, Asian fish tapeworm monitoring did not occur because of COVID-19 restrictions causing restricted access to the Little Colorado River on Navajo Nation lands. Infestation rates from 2015-2019 indicated relatively low incidence of infestation (average = 20% infestation) with typically only a single worm found per fish, whereas assessments conducted from 2005-2007 averaged 40% infestation, with up to 182 tapeworms found in a single fish. The reason for this apparent recent decline in Asian tapeworm infestation is unknown.

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

Invasive Aquatic Species Monitoring in Lees Ferry

To improve early detection of rare, nonnative species in Glen Canyon (Project Element I.2) AGFD conducts rare-nonnative monitoring twice a year (summer and autumn).

Goals and Objectives

The primary goal of the rare nonnative monitoring is to provide early detection of rare nonnative fish species in Glen Canyon. We target areas where rare nonnatives have been caught before and warmer water areas such as spring inflows and sloughs/backwaters.

Data collected from our standard monitoring (Project Element H.4) and rare nonnative targeting efforts provide some information on long-term status and trends of rare nonnatives, including brown trout (*Salmo trutta*), found in this reach of the Colorado River.

Results

During AGFD's rare nonnative sampling, 171 rare nonnative fish were captured including: 83 common carp, 20 brown trout, and 23 green sunfish (*Lepomis cyanellus*). Rare nonnative fish captured during AGFD's standardized sampling (Project Element H.4) in Lees Ferry consisted of 419 brown trout and 2 common carp. During nonnative sampling in July, the slough at RM -12 was blocked off and a three pass depletion sampling effort was conducted to generate a population estimate of common carp in the slough (n=102 [80-132 95 % confidence interval]).

eDNA Sampling

The purpose of this research is to detect the presence of new aquatic invasive species introduced into the Colorado River in Grand Canyon through tributary inputs, from Lake Powell, or upstream movement from Lake Mead. In FY 2019 we purchased 4 Geopump™ II eDNA sampling pumps with GCDAMP funds in preparation for a May-June 2020 sampling trip. The project PIs successfully obtained additional non-GCDAMP funding through the FY 2020-2021 USGS-USFWS Science Support Partnership (SSP) Program to fund costs associated with this project that were not granted in the work plan, including the cost of a principal investigator and technician salaries. GCMRC also obtained additional non-GCDAMP funding from the Bureau of Reclamation (Reclamation) Phoenix Area Office to fund the cost of a Grand Canyon river trip. Additionally, Reclamation provided funds directly to the US Forest Service (USFS), National Genomics Center for Wildlife and Fish Conservation to fund the cost of eDNA laboratory analysis for this project. In total, an additional $158,270 was obtained to be used along with the $7,438 in GCDAMP funds budgeted in the FY 2018-20 TWP to complete this project.

No eDNA samples were collected in May 2020 as originally planned due to COVID-19 and the associated closure of Grand Canyon National Park from March to June 2020 and restrictions on National Park Service launch permits for administrative trips. The trip was rescheduled to May 2021 due to these issues and to avoid higher turbidity associated with the typical timing of the onset of monsoon season in July. Despite this delay, some pilot eDNA sampling occurred from June-August 2020 in Lees Ferry and the western Grand Canyon in collaboration with the USFWS and USFS. This pilot sampling was focused on refining water filtration methods in order to improve detection of eDNA on sample filters in a sediment-laden system such as Grand Canyon. Samples are currently being processed at the USFS National Genomics Center and will inform our sampling methodology for 2021.

Project I.3. Assess the Risks Warm-water Nonnative Fish Pose to Native Fish

Goals and Objectives

The goal of this project is to evaluate impacts of invasive nonnative warm-water fish on humpback chub in both laboratory and field settings. The objective is to quantify the relative risks that each warm-water predator poses to native fish for both large-bodied predatory species such as channel catfish (*Ictalurus punctatus*) and smallmouth bass (*Micropterus dolomieu*) as well to small-bodied predators like fathead minnow (*Pimephales promelas*), red shiner (*Cyprinella lutrensis*), plains killifish (*Fundulus zebrinis*) and green sunfish (*Lepomis cyanellus)* using methods similar to those employed for past trials with rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*; Ward and Morton-Starner, 2015). Standardized methods allow comparison of relative predation risks. These data will allow managers to understand which warm-water invasive fishes are the most detrimental to humpback chub populations so that management efforts can be focused on those species that are the most problematic.

Results

In 2020, COVID-19 closures resulted in the cancellation of field efforts focused on marking channel catfish within the Little Colorado River to obtain population estimates. Instead efforts were focused on laboratory evaluations of predation risk. In 2020, the potential impacts of small-bodied predatory fishes on larval and juvenile humpback chub and the risks that common carp pose to survival of humpback chub eggs were assessed. In nine replicate trials conducted in 150 gallon tanks with cobble substrates, two common carp (mean = 340 mm TL, Range 279 - 426 mm TL) were allowed access to newly fertilized humpback chub eggs for a 24-hr period. Carp predation on eggs resulted in a 96% decrease in humpback chub eggs that survived to swim-up, compared with control tanks without carp present (Figure 1). These results suggest common carp may pose a significant risk to the survival of humpback chub eggs through predation.

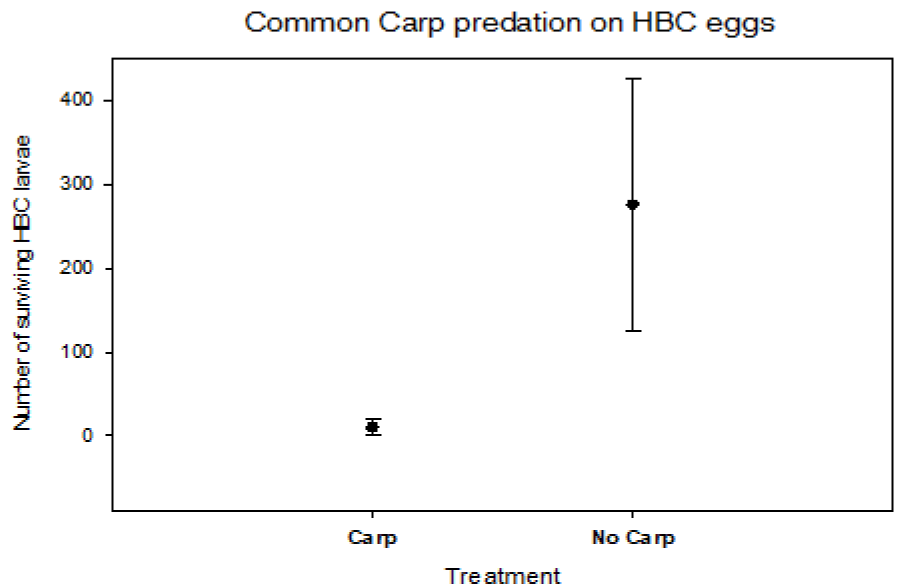

Figure 1. Number of humpback chub *Gila cypha* eggs that survived to produce larvae in laboratory tanks with and without common carp *Cyprinus carpio*. Results represent a total of nine replicated 24-hr predation trials.

Fathead minnow, red shiner, plains killifish and green sunfish are all currently found in the Little Colorado River and in the mainstem Colorado River downstream of Glen Canyon Dam. Although abundance of these small-bodied fishes varies on an annual basis, they have been shown to negatively impact native fish populations in other areas of the Colorado River Basin. Laboratory trials conducted in 2020 indicate that green sunfish are the most piscivorous of the small-bodied predators, followed by plains killifish, red shiner and fathead minnow. Risks from green sunfish predation appear to far outweigh the risks posed by the other small-bodied predators currently present in the Little Colorado River (Figure 2).

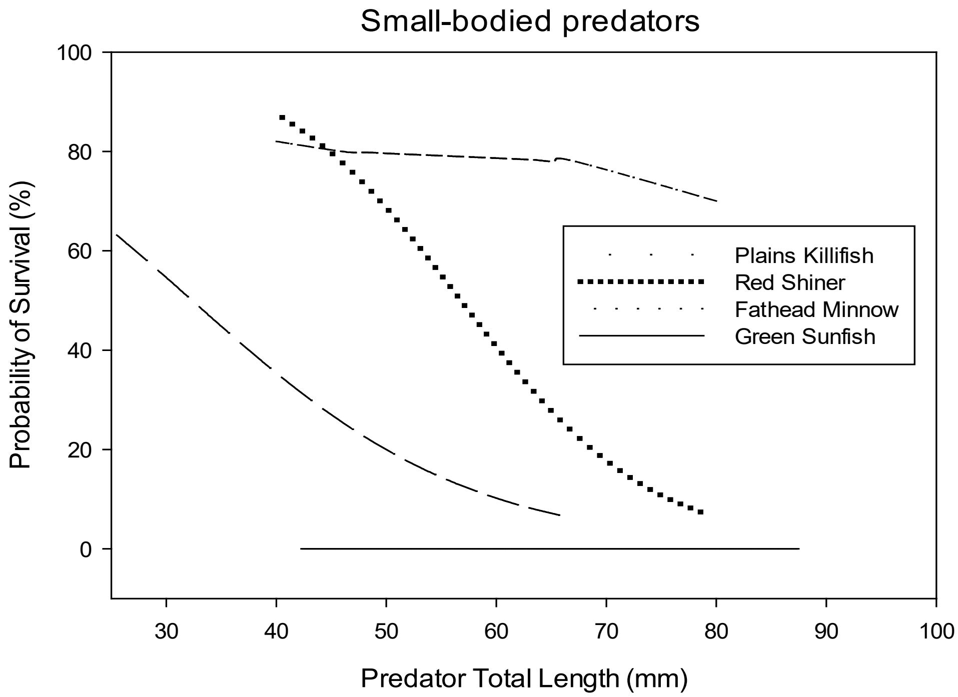

Figure 2. Survival of larval humpback chub *Gila cypha* (12 mm Total Length) as predator size increases for four species of small-bodied predatory fish commonly found in the Little Colorado River. Probability of survival calculated using JMP Prediction Profiler, based on 10 replicated 24-hr laboratory trials for each predator species (4 predators and 12 prey in each trial).

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Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$184,998	$2,500	$22,000	$238,550	$0	$36,055	**$484,103**
Actual Spent	$195,471	$2,976	$12,953	$173,508	$0	$34,366	**$419,274**
(Over)/Under Budget	**($10,473)**	**($476)**	**$9,047**	**$65,042**	**$0**	**$1,689**	**$64,829**
FY19 Carryover	**$213,932**					**FY20 Carryover**	**$278,761**

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

- Higher costs for salary were due to the inability to use as many volunteers as planned because of COVID-19 restrictions and had to rely on existing staff for field labor.
- Lower costs in operating expenses was due to the lack of a need to purchase equipment planned for field equipment and supplies for trips cancelled due to COVID-19 closures of the Colorado River in Grand Canyon and Navajo Nation lands.
- Lower costs in cooperative agreements was due to the requirement for GCMRC to receive approval from the USGS Director to fund the agreement which did not occur before the end of FY2020. GCMRC plans to transfer funds to the cooperator in FY2021.

Project J: Socioeconomic Research in the Colorado River Ecosystem

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Summary

The overall objective of Project J is to identify preferences for, and values of, downstream resources and evaluate how preferences and values are influenced by Glen Canyon Dam (GCD) operations. In addition, Project J is integrating economic information with data from long-term and ongoing physical and biological monitoring and research studies led by the USGS Grand Canyon Monitoring and Research Center (GCMRC). This integration will lead to the development of tools for scenario analysis that improve the ability of the Glen Canyon Dam Adaptive Management Program (GCDAMP) to evaluate and prioritize management actions, monitoring, and research.

Goals and Objectives

This project addresses the Tribal Resources, Humpback Chub (*Gila cypha*), Hydropower and Energy, and Rainbow Trout Fishery Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement resource goals by addressing the LTEMP Record Of Decision (U.S. Department of Interior, 2016a; U.S. Department of Interior, 2016b) objective to respect the “interests and perspectives of American Indian Tribes” and “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.” These studies also attempt to “maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term stability of downstream resources.”

Science Questions Addressed & Results

J.1. Tribal Perspectives for, and Values of, Resources Downstream of Glen Canyon Dam: Tribal Member Population Survey

Conducting socioeconomic studies of Tribal preferences for, and values of, resources downstream of Glen Canyon Dam is an important research element of the GCDAMP. Tribal socioeconomic studies allow insight into the preferences of Tribal stakeholders concerning resources management downstream of Glen Canyon Dam, the underlying reasons for the preferences, and the relative tradeoffs Tribal members are willing to make in the maintenance and improvement of downstream resources. This information is important to inform the prioritization of funding for monitoring and research in an adaptive management program.

The first phase of the tribal survey project was initiated in early 2017 as part of the Fiscal Years 2015-17 work plan. Initial tasks involved researching the current state of economic information pertaining to the five Tribes involved in the GCDAMP, as well as the broader issues of conducting natural resource survey research within a tribal setting. The second task, initiated in 2017 and carried into 2018, involved modifying the Glen Canyon Dam passive use survey instrument used in a national valuation study for use in a tribal setting (Duffield and others, 2016). The development of a modified survey specific to each Tribe was informed by formal meetings with representatives of the Hualapai Tribe, Hopi Tribe, Pueblo of Zuni, the Navajo Nation, and focus group meetings with the Hopi Tribe's and Pueblo of Zuni's cultural resource advisory groups. These meetings proved critical in the development of the tribal surveys in general, identifying critical flaws in design and implementation methods.

Following initial research, we implemented surveys on the Navajo Nation and with the Hualapai Tribe in 2019. A number of contact methods were considered for collecting survey data from Navajo Nation Tribal members. The challenges associated with implementing mail and phone surveys on the reservation led us towards employing a structured set of representative in-person group surveys at selected, geographically representative Chapters across the reservation. The Chapters are local government entities that historically represent local family or clan relations and were formally established to regulate grazing activities on the Navajo Nation. Presently, Chapters address grazing but also infrastructure, housing and social issues. Surveys on the Navajo Nation were facilitated through our participation in official Chapter meetings and subsequent use of Chapter facilities. Engagement with Chapters entailed several trips to the Chapter to request use of the facility and approval of the Chapter government for administering the group surveys. The group surveys were advertised in Chapter meetings, and participants were paid a $40 stipend for their participation in the approximately two-hour group survey. In total, between November 2018 and May 2019, group surveys were held at 12 Chapters and 289 individual tribal member surveys were collected though the process.

The Hualapai Tribal surveys were conducted September 23-25, 2019. Prior to survey implementation, pretesting of the survey occurred with Hualapai Department of Natural Resources staff and members of the Cultural Advisory Committee in November 2019. The Hualapai Tribal surveys were conducted in the community of Peach Springs at the Hualapai Cultural Center, Education and Training Center, and Elderly Center. As with the Navajo Nation, the challenges associated with implementing mail and phone surveys with the Hualapai Tribe led us towards employing a structured set of representative in-person surveys. Hualapai Cultural Center staff facilitated the implementation of the surveys. The in-person group surveys were advertised in news media, and participants were paid a $40 stipend for their participation in the approximately two-hour group survey. In total, 108 individual Hualapai Tribal member surveys were collected though the group survey process.

Both the Navajo Nation and Hualapai Tribal survey was divided into five sections. The survey began with initial questions on the importance of downstream attributes to the Tribal member. This set of questions was followed by a block of questions on the member's level of approval of the use of specific river flow management tools for protection or improvement of downstream resources. The second survey section was a one-page question on the willingness to pay for the implementation of the respondent's approved river flow management tools to protect downstream resources. A third large block of questions presented a set of nine discrete choice comparisons of two different sets of resource outcomes from river flow management and asked participants to choose which of each set they would prefer. Following the discrete choice questions, participants were asked two sets of Likert-scaled questions concerning their level of agreement or disagreement with a set of statements about Colorado River resources and their use. The second to last survey section asked a set of standard demographic questions followed by a set of open-ended questions allowing for additional comments by the participant. The final Navajo survey section asked respondents to report on general values associated with Grand Canyon and the Colorado River (two separate questions). These questions were asked first of the Hualapai. These questions asked respondents to share stories, experiences or other important information about the Grand Canyon and Colorado River. Results from the Hualapai Tribal surveys will be presented at the Annual Reporting meeting in January 2021, following approval from the Hualapai Tribal Council.

In 2020, we continued to engage with tribal representatives, researchers, and tribal members including a virtual presentation to the Navajo Nation Human Research and Review Board on July 30. The COVID-19 pandemic led to a postponement of engagement with Navajo Nation Chapters that participated in the survey. Condition dependent, we will engage with Navajo Nation Chapters, the Hualapai Cultural Advisory Team, Hualapai Cultural Center staff, and the Hualapai Tribal Council in 2021.

The Hopi Tribe, Pueblo of Zuni, and Southern Paiute Consortium have indicated that they will not participate in the survey. Continued engagement with the Pueblo of Zuni and Hopi Tribe, learning from survey implementation with the Navajo Nation and the Hualapai Tribe, and continued investigation into existing documentation and ethnographic material will potentially position researchers for additional insights into incorporating tribal perspectives and preferences into adaptive management.

J.2. Applied Decision and Scenario Analysis

In 2019, Donovan and others (2019) published an updated bioeconomic model to estimate the most cost-effective approach to managing rainbow trout removal at the confluence of the LCR and the Colorado River to meet long-term adult humpback chub survival goals. The Donovan and others (2019) paper refined previous work by Bair and others (2018), using novel dynamic programming methods to identify removal actions that cost-effectively met long-term adult humpback chub abundance goals. The updated model does not impose a predetermined structure on the shape of the policy function and removals are based on the abundance of rainbow trout in the juvenile humpback chub monitoring reach and the abundance of adult humpback chub in the Little Colorado River aggregation. This new framework also allowed for initial investigation into the value of information with respect to reducing uncertainty in the relationship between humpback chub survival and rainbow trout abundance. Results of the model are similar to the Bair and others (2018) simulation but are more effective and efficient at meeting humpback chub abundance goals because triggers are informed jointly by rainbow trout and humpback chub abundance.

In 2020, GCMRC and the US Fish and Wildlife Service collaborated to develop a model that evaluates the effect of Chute Falls translocations on adult humpback chub abundance and the change in expected number of rainbow trout removals to meet humpback chub abundance goals (Yackulic and others, *in review*). Model results indicate that continuous effort of translocating 200 juvenile humpback chub each year upstream of Chute Falls would be expected to result in an extra 246 (95% CI: 76-430) adult humpback chub under equilibrium conditions, compared to no translocations. Increasing the number of adult humpback chub reduces expected removals and associated costs of rainbow trout removals to meet adult humpback chub abundance goals (Figure 1). However, translocations are limited in their potential for increasing adult numbers thus necessitating trout removals in scenarios where humpback chub numbers plummet (Figure 1).

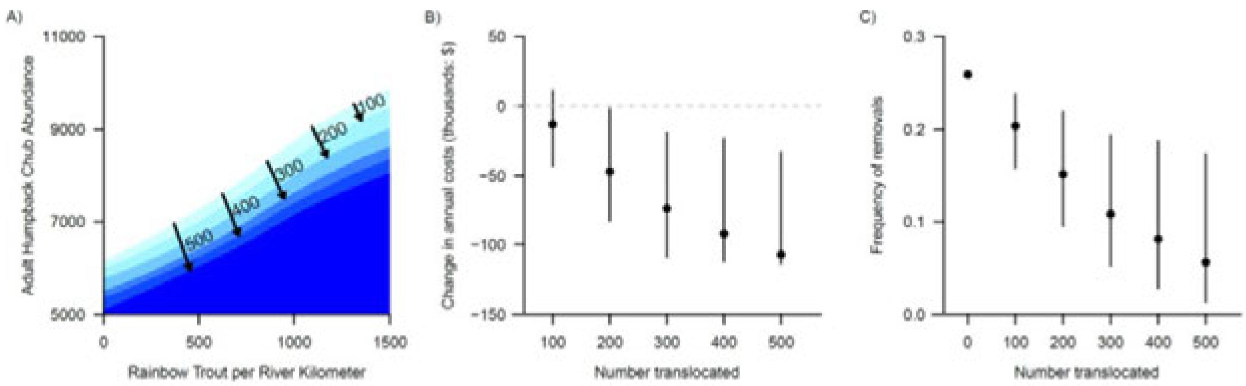

Figure 1 (Adapted from Yackulic and others, *in review*). Benefits of translocations depend on the number of humpback chub *Gila cypha* that are moved. (A) Increasing translocations change the optimal nonnative removal policy (arrows are average humpback chub translocation and rainbow trout *Oncorhynchus mykiss* removal triggers in blue), leading to decreased expected management costs (B) and a lower expected frequency of removals (C).

Lucas Bair and collaborators are expanding on the rainbow trout and humpback chub dynamic programming model to assess the effectiveness of trout management flows and the value of information with respect to reducing uncertainty in the relationship between trout management flows and mortality of juvenile rainbow trout. The Donovan and others (2019) model will also allow research into the impact of nonstationary climate impacts (e.g., changes in flood frequency) on humpback chub recruitment in the Little Colorado River and how that may inform effective and efficient management and research. This work is based on the Donovan and others (2019) model but also will rely on important research in biogeomorphic changes in the Little Colorado River (Dean and Topping, 2019) and humpback chub recruitment (Van Haverbeke and others, 2013). Extending the dynamic programing model described by Donovan and others (2019) in these ways could allow researchers to investigate the effectiveness and efficiency of flow management actions for other nonnative species, such as brown trout, in the Lees Ferry reach of the Colorado River.

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Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$141,904	$3,250	$1,125	$71,500	$0	$22,323	**$240,102**
Actual Spent	$138,036	$2,358	$2,516	$128,548	$0	$23,569	**$295,027**
(Over)/Under Budget	**$3,868**	**$892**	**($1,391)**	**($57,048)**	**$0**	**($1,246)**	**($54,925)**
FY19 Carryover	**$93,462**					**FY20 Carryover**	**$38,537**

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

- Lower costs in salary was due to part of the Principal Investigator's salary being covered by a non-GCDAMP project.
- Higher costs for operating expenses were due to the need to purchase additional supplies for Tribal meetings that had been delayed from a previous year.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project K: Geospatial Science and Technology

Project Lead	Tom Gushue	**Principal Investigator(s)** (PI)	Thomas Gushue, USGS, GCMRC Timothy Andrews, USGS, GCMRC James Hensleigh, USGS, GCMRC
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Summary

The Geospatial Science and Technology project (Project K) provides support to 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, web application development, and other tasks for online data resources. While some of the work performed in the FY 2018-20 Triennial Work Plan is an extension of efforts initiated in the FY 2015-17 Triennial Work Plan (Bureau of Reclamation and U.S. Geological Survey, 2014), some new efforts have also been initiated.

The level of support now being provided by this project for GCMRC extends into the application of relational databases, adopting and leveraging 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 the avenue for eventual inclusion into the USGS Cloud Hosting Solutions (CHS) environment within the Amazon Web Services (AWS) cloud platform, or other suitable endpoints, where appropriate. There is a shift in this support to now focus more on promoting GCMRC's abilities to move project data from the field to databases and then to predetermined endpoints such as the cloud in efficient, modern workflows that maintain some consistent elements and yet can be adapted to each project's unique properties. Specific accomplishments for FY 2020 are presented across the three Project Elements; however, it is important to note that there is often crossover in this support between Elements.

Project K staff have continued efforts in pioneering the AWS cloud environment for GCMRC, expanding on a new Internet of Things (IoT) sensor-to-cloud initiative, and furthering relational database and front-end application development that highlights the data of science projects. Most work performed within Project K falls within one of three main categories—Geospatial Data Analysis, Geospatial Data Management, and Access to Geospatial Data Holdings—although many work elements will have aspects that can be discussed in all three of these categories.

Over the past three fiscal years, the approach Project K has employed for GCMRC has had two underlying threads – 1) support GCMRC's 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 a project's data management, analysis and data access strategies, usually by leveraging newer technologies to achieve these goals. This project also strives to coordinate outside of the Glen Canyon Adaptive Management Program (GCDAMP) with USGS entities such as a newly formed Ecosystems Mission Area Information Technology Advisory Council (EMA ITAC), the USGS Enterprise GIS support team, USGS CHS—including the Tableau software (https://www.tableau.com/) and IoT-sensors User Groups in CHS, and the emerging Earth Monitoring, Analysis, and Prediction (EarthMAP) initiative for the USGS (Jenni and others, 2017).

Goals and Objectives

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

GIS Administration

GIS Administration tasks related to science support included the testing and migration of systems to newer versions of the most commonly used GIS and Remote Sensing software, maintaining licensing information and/or working with IT staff to ensure all licenses, software, extensions, add-ons, and custom applications work properly. This work includes the installation, configuration and administration of ESRI Desktop ArcGIS and Enterprise GIS software for GCMRC (ESRI, 2020a). Work performed through this project continued to support research and monitoring projects from Fiscal Years (FY) 2018-20 work plan (U.S. Department of the Interior, 2017) 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 all GIS-related work 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. Additionally, this project is responsible for handling data calls pertaining to a wide array of GCMRC's data resources every year.

Advances in Data Science Support

In FY 2020, GCMRC's use of Tableau data visualization expanded with 6 seats (3 Creator, 3 Data Viewer) of this software available to staff who have begun to build the capacity needed for creating compelling, database-driven analytical capabilities that have not previously been available to GCMRC.

This increased database and analytical capacity is leading to more efficient workflows for scientists and improves upon the access to these important data for managers and stakeholders within the GCDAMP.

GCMRC Projects Directly Supported in FY 2020

Research efforts that received direct support in geospatial and data tasks:

Lake Elevation Analysis Tool for Water Quality Monitoring of Lake Powell Tributary Inflow:

- Geospatial analysis performed to support the research ecologist for Lake Powell to develop a novel geospatial data analysis workflow to calculate surface area and volume for 67 tributary inlets to Lake Powell, in support of research focused on understanding contributors to Greenhouse Gas Emissions (GGE) from lacustrine environments.
- Work involved developing a process to use existing pre-dam Digital Elevation Model (DEM) data (see Figure 1) to calculate surface area and volume metrics given certain, user-defined parameters.
- A geoprocessing tool was developed using Python programming language to allow the user to run various scenarios of both the absolute range in lake elevations, and the elevation increment to be used in the analysis.
- Several analysis scenarios were devised and run against the DEM data for Lake Powell; the resultant data were provided to the researcher for inclusion into analysis of littoral area contribution to GGE at each specified tributary inflow site.

List of Projects with on-going GIS Support:

- Project B. Sandbar monitoring / Sediment storage
- Project C. Riparian vegetation monitoring
- Project E. Nutrients and Temperature
- Project G. Juvenile humpback chub monitoring in the Little Colorado River
- Project H. Glen Canyon fish monitoring
- Projects G, H and I. Downstream fish monitoring, including support provided to DOI partners (NPS GRCA, USFWS, BOR) and other stakeholders such as AZGF.

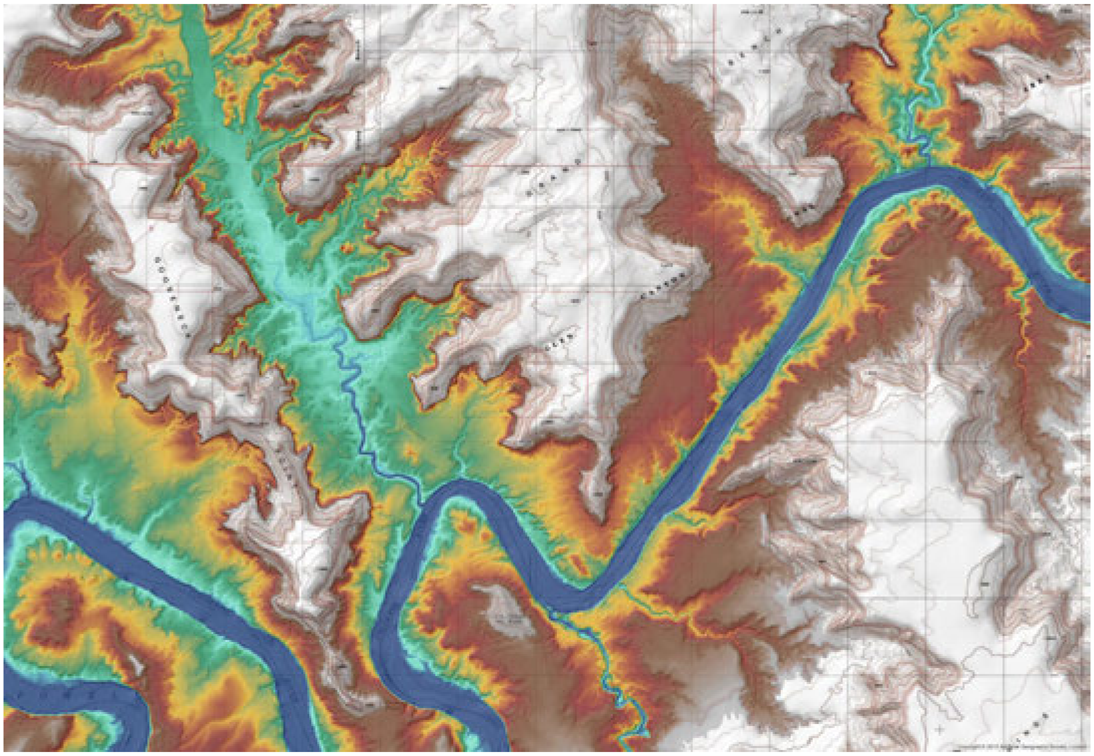

Figure 1. Screen view of Lake Powell pre-dam topography used as an input for a geospatial analysis tool to batch calculate area and volume for specified lake elevations. This topographic elevation data set was published in a USGS data release in 2019, https://www.sciencebase.gov/catalog/item/5c79a462e4b0fe48cb5144dc.

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

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 (Oracle, SQL Server) – as well as external clients that range from desktop applications (ArcGIS ArcMap, QGIS) to web-based endpoints (REST services, online applications, ArcGIS Online content, see Project Element K.3). Work performed within this project also includes many IT-centric tasks that were originally not a part of the GIS project in past work plans. In future work plans, this work will expand to include more broadly the theme of data management and database administration throughout GCMRC. Presented here are lists of projects support through database administration and software development, documentation and training already occurring during the FY 2018-20 Triennial Work Plan.

Database Administration Support to Projects

Lake Powell Water Quality Database

- Administered and maintained the water quality database.
- Worked with the research ecologist and hydrologist to improve upon how data are organized in the database, and how staff interacts with the data.
- Discovered, documented and resolved data issues.

Riparian Vegetation Survey Database (Project C)

- Administered and maintained the riparian vegetation survey database.
- Administered and maintained a database for Glen Canyon flow modeling outputs.
- Administered and maintained the survey accounting database.

Fish Monitoring (Projects G, H, and I)

- Initiated a review of the entire existing fish monitoring database workflow for GCMRC.
- Developed better documentation in the fish monitoring database on how fish monitoring is conducted and how the data are organized with cooperating agencies (USFWS, AZGF, NPS).
- Initiated a full documentation of existing relational databases used by fish biologists at GCMRC and other agencies (Oracle, Microsoft Access), determined how these databases were being used, and identified where improvements can be made to the workflow process.
- Migrated the fish monitoring database schema from Oracle to PostgreSQL.

Geodetic Control Database (Project B)

- Administered and maintained the geodetic control network database.

Sandbar Monitoring

- Administered and maintained the sandbar monitoring database.
- Maintained a system of daily automated backup of the master sandbar database.

General Database Functions (supports many projects)

- Maintained a system to automatically create weekly backups of every database on instance.
- Administered an SQL Server 2016 Express instance.
- Administered a MySQL Server instance.
- Administered and maintained an EPSG Spatial Reference database internally to serve as a resource when designing spatial systems.

Software Development, Documentation and Training

Project K staff led efforts to develop custom software applications designed to improve data entry, data editing, QA/QC, and reporting functions for specific science projects. Below is an annotated list of project support through this type of software development with some specifics included on the functionality of the applications:

Lake Powell Water Quality Database

- Administered and maintained the water quality database.
- Developed C# application, Water Quality Create, Read, Update and Delete (CRUD) application, to create, update, delete, filter, display, summarize, and output water quality data maintained by the GCMRC.
- Developed documentation for Water Quality CRUD and its backend database.
- Performed training and support to technician(s) and scientist(s) on how to use Water Quality CRUD.

Riparian Vegetation Survey CRUD (Project C)

- Maintained the C# application Vegetation Survey CRUD to create, update, delete, filter, display, summarize, and output data from vegetation surveys.
- Maintained the C# application Survey Accounting CRUD to create, update, delete, display, summarize, catalog and output data from GPS and terrestrial surveys not associated with the geodetic control network. This data comes from a variety of sources and geographic scope and provides support for data outside of the physical project.
- Performed training and support of biological staff working with vegetation survey data on how to use Vegetation Survey CRUD to load and maintain vegetation data.

Sandbar Monitoring (Project B)

- Maintained and provided bug fixes for the Sandbar Workbench C# software.
- Maintained and provided bug fixes for the Sandbar Analysis python scripts.
- Managed the transferring of new remote camera images to a new web server for use by web applications.

Geodetic Control and Survey Account CRUD (Project B)

- Maintained the Geodetic Control CRUD, a C# application to process, filter, display, summarize, and output data from the geodetic control network.

- Maintained the C# application Survey Accounting CRUD to create, update, delete, display, summarize, catalog and output data from GPS and terrestrial surveys not associated with the geodetic control network. This data comes from a variety of sources and geographic scope and provides support for data outside of Project B.

SBSC-wide Support

- Maintained text and graphical documentation of the CHS AWS environment, applications within GCMRC's environment, and the components used to build the applications.
- Performed training and support to GCMRC staff on the use of and best practices for use of our AWS environment.
- Maintained a series of C# Dynamic Link Library (DLL) files that provided support for processing coordinates, creating spatial datasets, and processing Trimble survey files. These DLL files are being used by multiple production C# applications.
- Maintained a standard python script template and associated modules to automatically provide consistent logging and argument parsing.

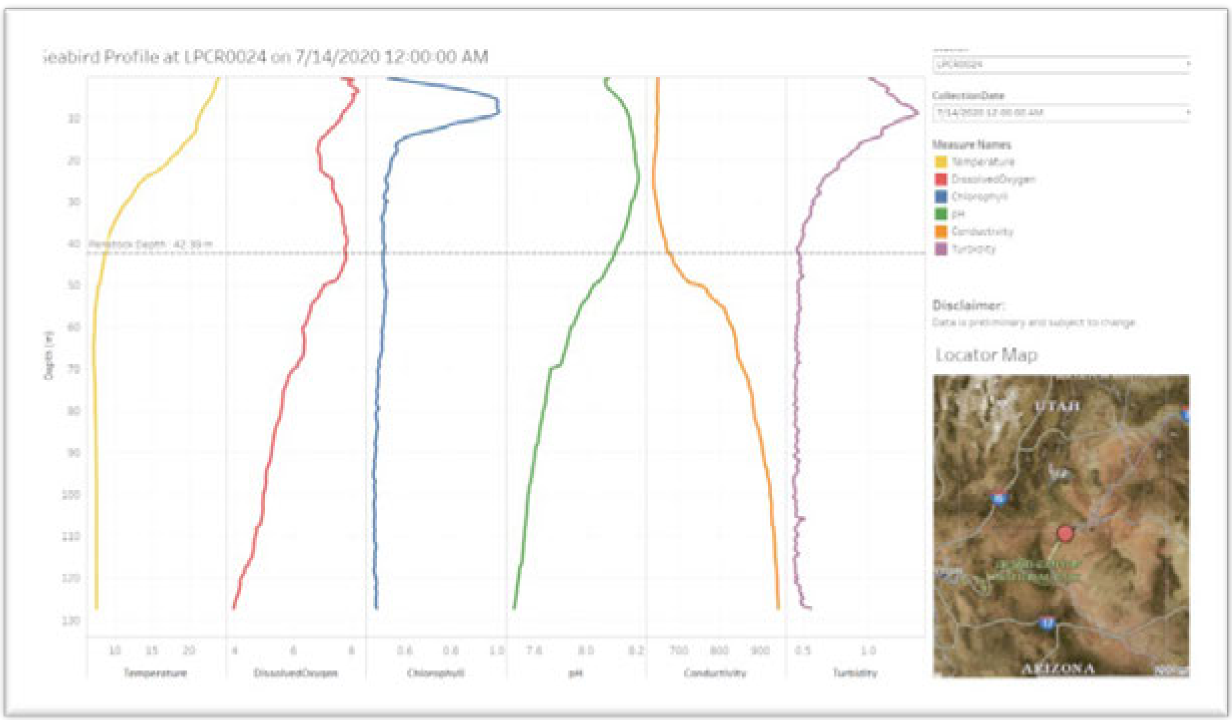

Figure 2. Data visualization of Sea Bird profile data for a specific sample site in Lake Powell. Data shown here are from the July 2020 site visit, which are stored in a newly designed Microsoft SQL Server database and connected to the Tableau Server software through a live data link.

Expansion of Cloud Environment Usage for Science Project Support

Another example of the expanded role in data management is the effort to advance GCMRC into the AWS cloud environment. This work involved coordination at a high-level with GIS and IT staff at the 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 developed GCMRC's capacity for working in and building applications for the Amazon cloud environment,
2. Acquired additional licenses for and began working with new data visualization software (Tableau Desktop and Server) that allows GCMRC staff to connect to a variety of data sources (static files, spreadsheets, relational databases, online services, etc.) and develop custom, advanced data visualizations of their project's information, and
3. Advanced the data visualization capabilities for at least one GCMRC project through the use of Tableau Server in AWS (see Figure 2 for example).

In FY 2020, we were able to achieve all three of these goals. Some specifics that were achieved related to these goals include the development and implementation of a repeatable integration/continuous development (CI/CD) pipeline to deploy applications to AWS, and the development of a public Simple Storage Service (S3) bucket that can be used to serve photos and replace out-of-service web servers previously being used for same purpose.

Expanding Use of Source Control

Project K has continued to lead GCMRC in developing and managing geoprocessing scripts, web applications and other work involving programming through online source control and versioning platforms. This work included migrating and consolidating existing code based to USGS-approved platforms: USGS GitLab (https://code.usgs.gov) and USGS CHS GitLab (https://code.chs.usgs.gov). This effort has led to greater efficiency in code development, geoprocessing task performance, and faster development of new web applications than previously possible. By spearheading this shift to 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.

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

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/index.html).

This work involved configuring, testing and publishing new geospatial data sets to the Grand Canyon Geospatial Portal that directly support new science project information and findings. This included working with other USGS IT entities to resolve web-based applications and other online content issues and improve performance in delivering GCMRC geospatial content online.

System Migrations to New OS

A major effort in this area was to handle a national system security directive within the DOI to migrate all systems to newer operating systems. While this is rather simple for desktops and laptops, it is more involved for servers that handle live access to our geospatial content. In FY 2020, this project was able to rebuild the external GIS Portal to a new, more advanced system. Work remains on restoring (or redesigning) all content services that existed prior to the migration.

In FY 2020, the data serving aspects of this project required a larger amount of web server system migration and configuration, back-end database migrations, and associated updates to web services and applications hosted by GCMRC than in previous fiscal years. This included the development of a new data serving portal, now called the Grand Canyon Geospatial Portal (see Figure 3), built on newer server hardware with the latest, approved operating system, Windows Datacenter 2019. This was a necessary migration as the previous Portal hardware and operating system had been extended as far as possible and were nearing outside-of-lifecycle status. Additionally, the Oracle spatial database used to store, organize, compress and serve GCMRC's geospatial data holdings had to be migrated to a newer computer system. An important note to add is that these migrations and new deployments were strategically planned to minimize downtime to these platforms and data services, and have been designed to utilize the existing URLs as much as possible to allow for a smooth transition. For instance, the new Portal still uses the same URL.

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

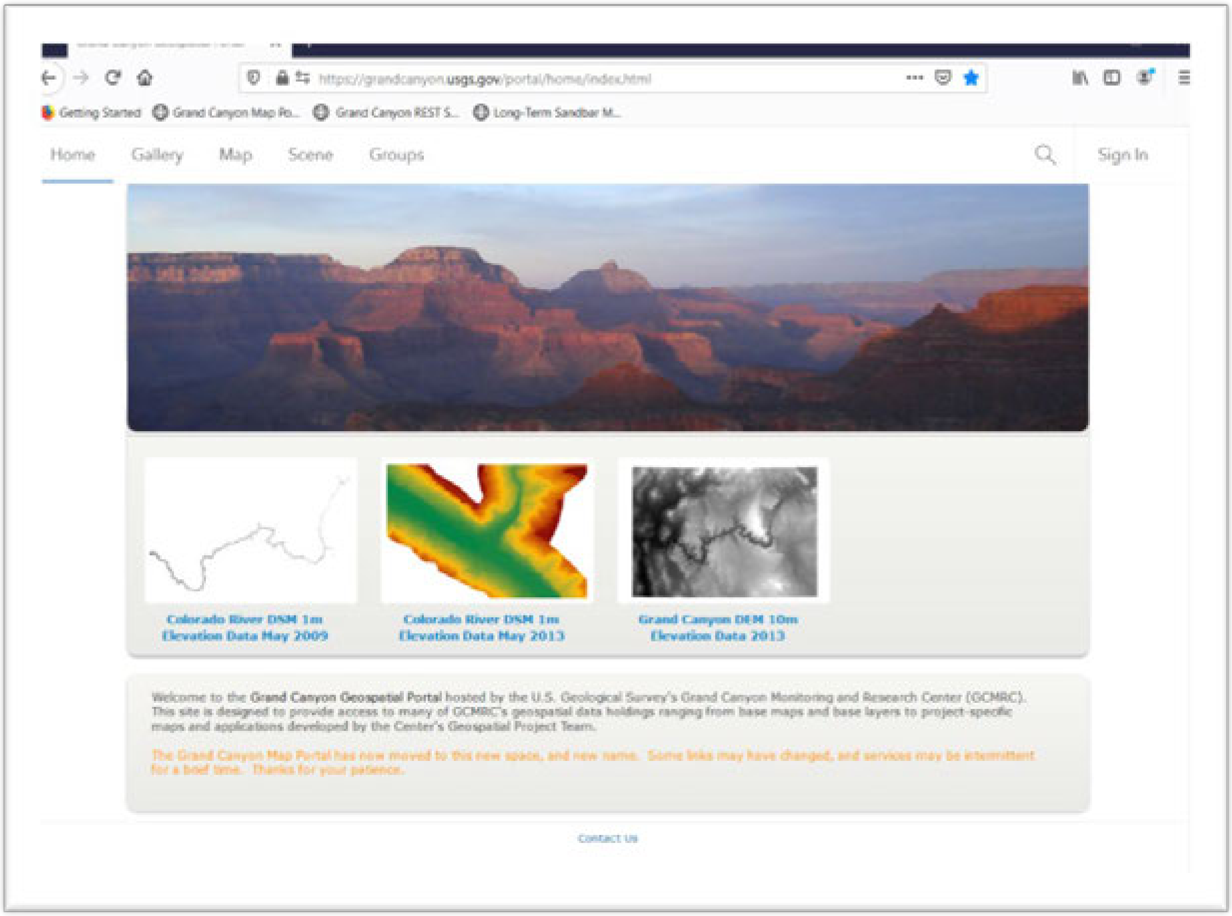

Figure 3. Screen view of home page for the new Grand Canyon Geospatial Portal designed to serve GCMRC's geospatial content online.

Newly Upgraded Web Applications hosted in ArcGIS Online

Once the new data serving software had been installed, configured and was operating successfully, then many of the existing web mapping services had to be updated to account for minor changes in connection protocols and URL path refinement. Below is a partial list of existing applications that are still available on ArcGIS Online now that those upgrades have been completed:

Predicted Shorelines for High Flows on the Colorado River Application

Sandbar deposition following the 2018 High-Flow Experiment

Campsite Atlas Web Application

The benefit of using ESRI ArcGIS online (ESRI, 2020b) in addition to hosting our own geospatial portal is that a particular service only needs to be created once by GIS staff, but can then be posted on both GCMRC's website and through ArcGIS Online to reach a wider audience. The link below provides access to all publicly available content hosted by GCMRC on ArcGIS Online.

Access to Geospatial Data Holdings – ESRI's ArcGIS Online:
http://usgs.maps.arcgis.com/home/search.html?q=GCMRC&t=content

UPDATED Geospatial Services page:
https://grandcanyon.usgs.gov/gisapps/restservices/index_wret.html

We continue to provide access to GCMRC's geospatial data sets through a web services directory page that organizes Representational State Transfer (REST) service endpoints by data set and resource type. Web services and applications built on the REST architectural style have standardized methods for interacting with the data content and are optimized to work best on the web. These services can be used in desktop applications by downloading a link (*.lyr) file of any service. They can also be accessed in web applications developed by users outside the GCMRC, or added into other programs, such Google Earth, as a layer on the map.

The Geospatial Services page was updated in FY 2020 to leverage the newer front-end ArcGIS Server application and associated back-end Oracle relational database that hosts and serves the data. This process involves updating both ArcGIS Server and Portal applications on an external-facing webserver to make the most current functionality available provided by these platforms at the time, and updating map services to the latest version allows for better desktop-client compatibility for users.

These services take advantage of new functionality that is available to geospatial data at this version, while still being backwards-compatible with 10.x versions of ESRI ArcGIS desktop software. Additionally, many of the geospatial services are being offered as Web Map Services (WMS) as defined by the Open-source Geospatial Consortium (OGC), which means that many of GCMRC's geospatial data sets can be accessed by anyone through open-source software and custom-built applications. This fact increases both the importance of GCMRC's Enterprise GIS platform, and the visibility of our work to a much wider audience.

IoT Sensor-to-Cloud Data Transmission

We expanded the SBSC's use of the USGS CHS environment and provided unparalleled opportunities for SBSC/GCMRC science staff. Despite experiencing unprecedented challenges due to the COVID-19 pandemic in 2020, we were still able to advance GCMRC's use of new technologies, including expanding plans for instituting IoT technology in multiple study sites. This work has SBSC and GCMRC well positioned for a renewed interest in IoT technologies from USGS leadership and was presented on in September 2020 as a part of the USGS Rocky Mountain Region's Science Exchange Workshop that was focused on the emerging EarthMAP initiative within USGS. In FY 2020, we improved our ability to interact with field-base sensors through the Amazon Web Services IoT cloud environment, and expanded connected sensors to include a water quality monitoring sensor located at the USGS Lees Ferry gaging station (USGS 09380000 Colorado River at Lees Ferry, AZ). The data are sent via a wireless ethernet connection to the base access point at Lees Ferry. By leveraging the power of cloud computing, data parameter values can be observed in near real-time in the form of data packets sent to the cloud broker (Figure 2) and shown on custom data dashboards developed to track changes in data parameters over time (Figure 4).

Figure 4. A screenshot of Thinglogix Foundry application showing water quality data from the Colorado River at Lees Ferry (River Mile 0) streaming to Amazon Web Services cloud environment. The sensor came online in January 2020, and data are recorded every 4 minutes then sent to the cloud via cellular MQ or "machine-to-machine" Telemetry Transport (MQTT) protocol every 15 minutes.

Science Questions Addressed & Results

Project K does not address specific science questions or hypotheses since it is inherently a supportive effort for GCDAMP-funded projects and a SBSC-wide resource for geospatial and data management functions. However, this project has delivered critical support across GCMRC including services such as data processing, data management and documentation, and geospatial processing and analysis which are essential to the success of nearly all projects. The following justifications have been used to guide Project K during the FY 2018-20 work plan:

- Data management, including geographic information systems (GIS), has been a part of GCMRC's role in GCDAMP since its inception, and was also supported in the 1995 ROD – specifically in GCDAMP Goal 12, to maintain a high-quality monitoring, research and adaptive management program (U.S. Department of Interior, 1996).
- Subsequent documents, including the most recent LTEMP, have reaffirmed this important aspect of GCMRC and the GCDAMP (U.S. Department of Interior, 2016a).
- Project K is designed to support the other proposed science projects that are aligned with resource goals identified in the LTEMP and in more recent DOI guidance where both documents call for continuity in resource monitoring and consistency in providing high-quality monitoring and research to the GCDAMP (U.S. Department of Interior, 2016a; Petty, 2019).
- Project K works to share important information about trends in resources of the Colorado River ecosystem through web-based, interactive tools and mapping products (VanderKooi and others, 2017).
- Project K allows for the ability to make better informed, time-sensitive decisions on experimental and management actions under the 2016 LTEMP and the associated ROD (U.S. Department of Interior, 2016a, b).

FY 2018-20 Summary

Provided here is a brief summary of accomplishments from this project over the past three fiscal years. The overarching goals put forth by Project K for the FY 2018-20 work plan include the items listed below and have directly benefited many of GCMRC's science projects over the past three years.

- Improved web presence for GCMRC, with current information and more content available online.
- Assisted more projects with data management and relational databases than in previous work plans.
- Modernized access to data from field-based sensors and worked to continually improve long-term monitoring of key riparian resources, specifically water quality, suspended sediment, aeolian sand transport, and soil moisture.

Migration of GCMRC website

Project K led and migrated GMCRC's static web content away from its old website (https://www.gcmrc.gov) and into the new USGS-approved web content management system. This work included understanding the back-end architecture upon which the content management system was built, designing web pages, linkages, and related content to be hosted on the new website, and coordinating and communicating with the web re-engineering team (WRET) on how best to get their platform to work for SBSC and GCMRC's unique situation.

This work also included identifying and documenting the web redirect links that would be applied through the USGS National Web Server System (NatWeb) for GCMRC's legacy website and web pages to be properly ported to the new USGS content management system hosted in the cloud. Additionally, this project directed and performed the work to apply the WRET-approved web content to GCMRC's existing online web applications. This work led to a seamless transition for GCMRC's online presence into the larger USGS content management system.

The new URL for GCMRC's Home Page is located here: https://www.usgs.gov/centers/sbsc/gcmrc

GCMRC Data and Tools Web Page on USGS WRET-Compliant website (Updated FY 2020)

Among the new web content created by Project K is a "GCMRC Data and Tools" landing page that provides a collective online location for finding dynamic web content and other data resources (Figure 5). This new web page can be accessed from GCMRC Home Page under the right panel labelled "GCMRC / RES Quick Links", or by going directly to this URL: https://www.usgs.gov/centers/sbsc/science/gcmrc-data-and-tools.

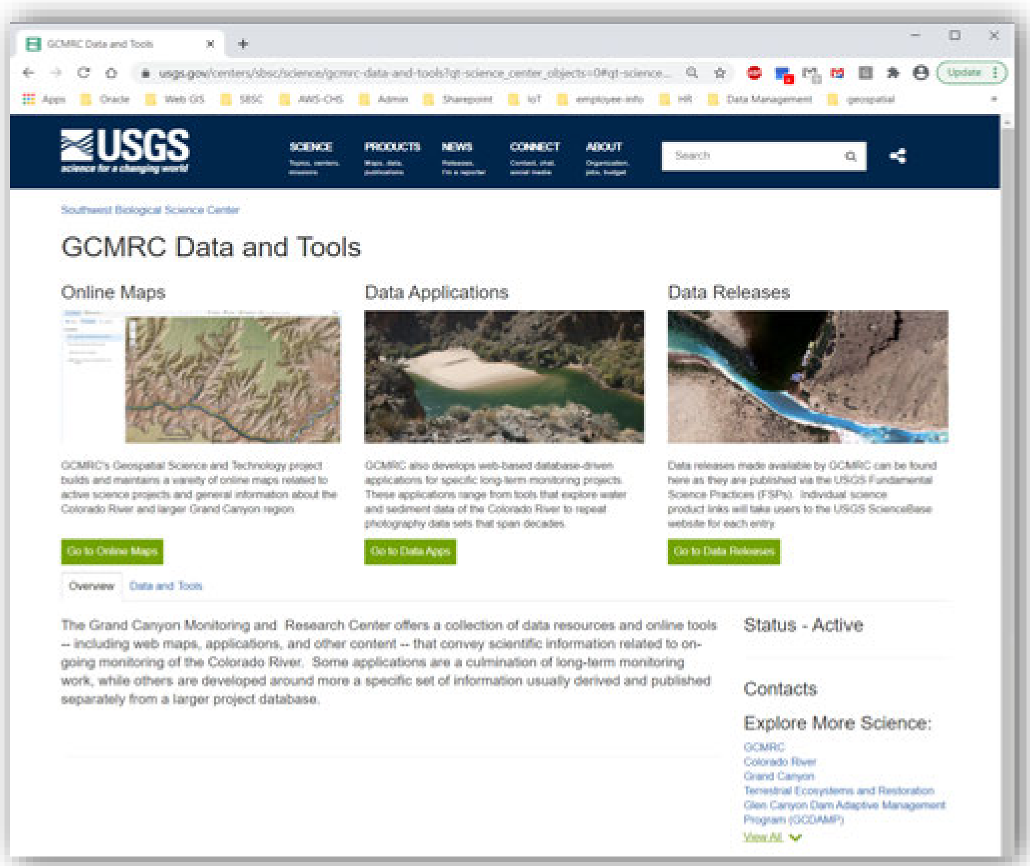

Figure 5. A screenshot of GCMRC's Data and Tools landing page. Available content is categorized between Online Maps, Data Applications and Data Releases.

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Budget

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$260,304	$4,000	$11,850	$0	$0	$38,093	**$314,247**
Actual Spent	$206,947	$0	$14,301	$0	$0	$30,519	**$251,767**
(Over)/Under Budget	**$53,357**	**$4,000**	**($2,451)**	**$0**	**$0**	**$7,574**	**$62,480**
FY19 Carryover	**$53,497**					**FY20 Carryover**	**$115,977**

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

- Lower costs in salary was due to a vacancy. Position will be refilled in FY2021.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs for operating expenses were due to the need to purchase new equipment that had failed.

Project L: Overflight Remote Sensing in Support of GCDAMP and LTEMP

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC
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Summary

The remote sensing overflight described in Project L has been postponed and is proposed to occur in May 2021 (tentative mission start date May 28, 2021). The overflight was postponed so that funding could be applied to other projects during the Fiscal Years (FY) 2018-20 work plan. Note that the cost of contract with the vendor for the overflight in 2021 is estimated to be $450,000 which covers imaging of the river corridor from Glen Canyon Dam to Pearce Ferry (including the rapid which is downstream of the boat ramp). To pay for the contract, $150,000 was retained by Bureau of Reclamation from the current 5-year agreement, and GCMRC has identified $75,000 from FY 2020 funding that will be carried over to FY 2021. Thus, Project L of the FY 2021-2023 Triennial Work Plan will require $225,000 in FY 2021 to pay for the remainder of the contract (i.e., $450,000 - $150,000 - $75,000 = $225,000). As noted in the FY 2021-23 Triennial Work Plan, GCMRC will redirect logistics funds from river trips cancelled in FY 2020 due to the COVID-19 pandemic and associated closure of the Colorado River in Grand Canyon and carried forward into FY 2021 to offset costs for the remainder of the contract.

Budget

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$0	$0	$0	$75,000	$0	$0	**$75,000**
Actual Spent	$0	$0	$0	$0	$0	$0	**$0**
(Over)/Under Budget	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$0**	**$75,000**
FY19 Carryover	**$225,000**					**FY20 Carryover**	**$300,000**
COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*							
- Lower costs in cooperative agreements was due to planned carryover of funds budgeted in FYs 2018, 2019, and 2020, in the amount of $75,000 each year, in support of the remote sensing overflight of Grand Canyon planned for FY2021. Funds were deobligated to Reclamation and will be held there until needed to fund the overflight.							

Project M: Administration

Project Lead	Scott VanderKooi, Chief	**Principal Investigator(s)** (PI)	Scott VanderKooi
Email	svanderkooi@usgs.gov		
Office	928-556-7376		

Summary

During Fiscal Year 2020, the budget for this project 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 salary for a technical information specialist and 80% of salary for a budget analyst. The vehicle section of the budget covers the costs associated with Interior-owned and GSA-leased vehicles that Grand Canyon Monitoring and Research Center (GCMRC) uses for travel and field work. Costs include fuel, maintenance, and repairs for Interior-owned vehicles and monthly lease fees, mileage costs, and any 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 two Partners in Science river trips conducted in FY 2018 and 2019 during which they educated youth participants in Colorado River science and directed them in data collection efforts in support of the FY 2018-20 Triennial Work Plan. Data were collected in support of understanding geomorphic processes of sandbars (Projects B and D), riparian vegetation (Project C), aquatic invertebrate ecology (Project F), the biology and ecology of native and nonnative fishes including humpback chub (Projects G and I), and rainbow trout (Projects H). No trips occurred in FY 2020 due to the COVID-19 pandemic.

Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$683,711	$42,000	$236,000	$0	$0	$132,658	**$1,094,369**
Actual Spent	$651,953	$17,145	$288,568	$0	$0	$132,100	**$1,089,766**
(Over)/Under Budget	**$31,758**	**$24,855**	**($52,568)**	**$0**	**$0**	**$558**	**$4,603**
FY19 Carryover	**$54,940**					**FY20 Carryover**	**$59,543**

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

- Lower costs in salary due to a staff member serving on a detail and USGS providing some funding for GCMRC leadership salaries in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2021 funding.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs in operating expenses due to the requirement of USGS to pay contract administrative fees associated with a labor dispute with the Department of Labor regarding salary rates in GCMRC's boat operations contract.

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$267,078	$6,000	$905,786	$11,000	$0	$162,943	**$1,352,807**
Actual Spent	$272,192	$2,474	$1,232,757	$11,000	$0	$208,264	**$1,726,687**
(Over)/Under Budget	**($5,114)**	**$3,526**	**($326,971)**	**$0**	**$0**	**($45,321)**	**($373,880)**
FY19 Carryover	**$381,337**					**FY20 Carryover**	**$7,457**

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

- Higher costs in salary due to retaining a retiree part time to help train new Logistics Coordinator.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs for operating expenses were due to needed field staff for several project being provided by contractors instead of USGS employees which are funded through GCMRC's boat operations contract.

Project N: Hydropower Monitoring and Research

Project Lead	Lucas Bair	**Funded Principal Investigator(s)** (PI)	Lucas Bair, USGS, GCMRC
Email	lbair@usgs.gov		
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Summary

The overall objective of Project N is to identify, coordinate, and collaborate on monitoring and research associated with operational experiments at Glen Canyon Dam (GCD) and opportunities to meet hydropower and energy resource objectives, as stated in the Long-Term Experimental and Management Plan Record of Decision (LTEMP ROD; U.S. Dept. of Interior, 2016).

Goals and Objectives

Operational experiments include those proposed in the LTEMP Environmental Impact Statement (EIS; e.g., High-Flow Experiments, macroinvertebrate production or “Bug Flows,” Trout Management Flows) or experiments that improve hydropower and energy resources (e.g., change in ramp rates, change in daily flow range, fluctuating flow factors, monthly volume patterns), while consistent with long-term sustainability of other downstream resources. The operation of GCD to meet hydropower and energy resource objectives, as the integration of renewables and a greater recognition of the social cost associated with power system emissions occurs, is an important consideration when attempting to maintain and improve resources downstream of GCD.

Science Questions Addressed & Results

In 2018 and 2019, Lucas Bair collaborated with researchers at Northern Arizona University (NAU) to identify the impact of proxy flow experiments on generation and emissions costs in the coordinated electricity grid in the western United States, Canada and Mexico. The ongoing collaboration utilizes existing research in power system modeling at NAU (Bain and Aker, 2017). This collaboration provides foundational research to meet the objectives of Project N which are to estimate and attempt to minimize impacts of proposed experiments in the LTEMP EIS on hydropower as part of the experimental design. To minimize impacts to hydropower and energy resources, cost production modeling was used to estimate the change in total economic value of hydropower generated at GCD under various future scenarios.

The total value of hydropower generated at GCD includes costs associated with energy generation, greenhouse gas emissions, human health, and other regional impacts. These impacts are dependent on the price of fuel (e.g., natural gas) and the integration of additional generation, including renewable energy, into the electricity sector. Scenarios incorporating these factors were used to assess total economic costs associated with a proxy experimental flow at GCD.

We demonstrated the change in production and emissions costs in the Western Interconnect by reoperation of GCD has the potential to be significant and could potentially result in offsetting costs. This example illustrates the importance of incorporating external social costs in environmental decision making and consideration of the technical characteristics of future power system expansion when managing resources downstream of GCD. Based on power system modeling in the LTEMP (U.S. Dept. of Interior, 2016), our hypothesis was that consideration of total costs (energy generation and emissions) when evaluating alternative flows at GCD will significantly change the results of the economic outcomes of experimental flows. For more detail in the preliminary results see the 2019 Annual Report or the corresponding presentation at the 2020 February AMWG Meeting.

In 2020, Lucas Bair collaborated with GCMRC's Bridget Deemer and researchers at the Environmental Protection Agency to estimate emissions per MWh at Lake Powell, informed by results of a survey of greenhouse gas emissions on Lake Powell and several global scale models that estimate greenhouse gas emissions from Lake Powell. While emissions per MWh were low in Lake Powell as compared to other conventional energy sources, the sensitivity of GHG emissions to reservoir water levels highlighted the potential importance of considering these dynamics in the design and operation of arid region reservoirs. For additional information, including a figure of the relative emissions per MWh, see Appendix 1: Lake Powell Water Quality Monitoring of this document.

In FY 2021, GCMRC will continue to coordinate with internal and external partners, including Western Area Power Administration and the 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 research is also being coordinated with the evaluation of hydropower costs associated with Trout Management Flows and other experimental flows.

References

Bair, 2020, Identifying the total economic value of hydropower at Glen Canyon Dam and implications for adaptive management—presentation at Glen Canyon Dam Adaptive Management Program Technical Work Group Annual Reporting meeting, January 13-15, 2020: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReprotingMeeting-IdentifyingTotalEconomicValueHydropowerGlenCanyonDam-Presentation-508-UCRO.pdf.

Bain, D.M., and Acker, T.L., 2018, Hydropower impacts on electrical system production costs in the southwest United States: Energies, v. 11, no. 2, article 368, p. 1-21, https://doi.org/10.3390/en11020368.

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

Budget

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$9,863	$750	$375	$0	$0	$1,516	**$12,504**
Actual Spent	$9,860	$0	$0	$0	$0	$1,360	**$11,220**
(Over)/Under Budget	**$3**	**$750**	**$375**	**$0**	**$0**	**$156**	**$1,284**
FY19 Carryover	**$686**					**FY20 Carryover**	**$1,970**
COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*							
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.							

Appendix 1: Lake Powell Water Quality Monitoring

Program Manager (PM)	Bridget Deemer	**Principal Investigator(s)** (PI)	Bridget Deemer, USGS, GCMRC
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Summary

Grand Canyon Monitoring and Research Center (GCMRC) has conducted a long-term water-quality monitoring program of Lake Powell and Glen Canyon Dam (GCD) releases in collaboration with the Bureau of Reclamation (Reclamation) and National Park Service (NPS). This project has been funded entirely by Reclamation from power revenues and receives no monetary support from the Glen Canyon Dam Adaptive Management Program (GCDAMP). In addition to direct funding of the program, Reclamation also provides support for laboratory analyses. 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.

Goals and Objectives

In Fiscal Year (FY) 2020, the USGS's GCMRC collected physical, biological, and chemical data and samples from Lake Powell, GCD, and Lees Ferry. GCMRC also continued to develop a new structured query language (SQL) based database platform that will house existing data and provide a more streamlined data entry process for newly generated data. A new interagency agreement was signed in FY 2018, which has supported GCMRC involvement in the Lake Powell Water Quality Monitoring program over the past three years with the potential for funding for two more years. In addition to fulfilling basic monitoring activities, GCMRC has collaborated with Dickinson College towards initial analysis of the long-term plankton data set at the Wahweap station. Collaboration with the Environmental Protection Agency has also supported greenhouse gas emission measurements from Lake Powell. Finally, historical data analysis conducted in FY 2018 and 2019 shows that Lake Powell has been functioning as a long-term calcite sink, resulting in salinity retention comparable to that achieved by efforts implemented as part of the Colorado River Basin Salinity Control Act.

Monitoring Activities

Water-quality monitoring was conducted by Reclamation from 1964 to 1996. Since 1997, the GCMRC and Reclamation have continued water quality monitoring with assistance from NPS under a cooperative agreement funded via the Water Quality group in the Upper Colorado Regional Office of Reclamation. Sampling protocols and sampling sites are summarized in USGS Data Series reports 471 and 959 (Vernieu, 2015a; Vernieu, 2015b). For most years since 1997, the sampling program has consisted of monthly sampling in the forebay area immediately upstream of GCD, in the GCD draft tubes, and in the GCD tailwater (at Lees Ferry), quarterly surveys of the entire reservoir, and continuous monitoring of GCD releases via two water quality sondes, one connected to an active penstock and one directly below the dam. Quarterly reservoir surveys have typically been conducted within a six-day time period. Monitoring during these surveys has consisted of field observations of weather conditions, Secchi depth measurements, vertical depth profiles of temperature, specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll concentrations at up to 35 locations on the reservoir, and sampling for major ions, dissolved organic carbon, and nutrients at a subset of these locations. In addition, biological samples for chlorophyll, phytoplankton, and zooplankton have been collected near the surface at selected stations.

Table 1. Beginning dates and sampling activity for the Lake Powell water-quality monitoring for FY 2020.

Date	Sampling Activity
10/8/19	Forebay, draft tubes, Lees Ferry
11/6/19	Forebay, draft tubes, Lees Ferry
12/10/19	Quarterly survey
1/24/20	Forebay, draft tubes, and Lees Ferry
2/18/20	Forebay, draft tubes, and Lees Ferry
3/17/20	Draft tubes and Lees Ferry
4/20/20	Forebay, draft tubes, and Lees Ferry
5/18/20	Forebay, draft tubes, and Lees Ferry
06/8/20	Abbreviated quarterly survey
7/14/20	Forebay, draft tubes, and Lees Ferry
8/25/20	Forebay, draft tubes, and Lees Ferry
9/18/20	Abbreviated quarterly survey

In FY 2020, Reclamation conducted one complete reservoir-wide survey and two abbreviated reservoir-wide surveys with involvement from GCMRC (Table 1). In addition, GCMRC conducted eight complete forebay surveys and one partial survey to supplement the quarterly surveys (Table 1). The reservoir-wide sampling was significantly reduced from the traditional quarterly survey design and the typical spring quarterly trip was canceled because of COVID-19 related travel restrictions. GCMRC also maintained two sonde instruments monitoring GCD releases. Results from laboratory analyses of samples are usually received within two months of collection; however, COVID-related laboratory closures caused longer hold times for chlorophyll a, nutrient, and major ion samples collected between March and August of 2020. As per protocol, chlorophyll a samples were kept frozen, major ion samples were kept refrigerated, and nutrient samples were kept acidified and refrigerated until analysis. A lapse in the contract between Reclamation and BSA Environmental Services, Inc. also caused a lapse in the processing of phytoplankton and zooplankton samples from July 2019 to September 2020. During the lapse, the samples were stored preserved in lugols in the dark at room temperature. The contract has since been awarded and sample shipment to BSA Environmental Services resumed in November 2020.

In FY 2020, significant progress was made towards an updated Lake Powell water quality database and data release. The formerly maintained Microsoft Access database has now been transferred to a Microsoft SQL Server database and a custom application has been designed that allows for streamlined data import and export. The database is still in testing and development, but data entry is largely up to date and a data release is expected in late FY 2021. The database is also linked to Tableau, an online data visualization platform. USGS scientists are currently developing data visualizations to share with their colleagues at Reclamation (Figure 1), with the eventual intention to make some visualizations public with the data release. Reclamation also uses a subset of the water quality data to run the CE-QUAL-W2 model (a 2D water quality and hydrodynamic model) and to create cross-section time series visualizations of reservoir temperatures, dissolved oxygen, pH, and total dissolved solids.

In March of 2018 a thermistor string with 17 Hobo temperature loggers and 2 Hobo conductivity loggers was deployed off the buoy line near GCD. Temperature loggers are deployed at 1m, 5m, 10m, 15m, 20m, 25m, 30m, 35m, 40m, 50m, 55m, 60m, 70m, 80m, 90m, 100m, and 120m with conductivity loggers at 45m and 110m. The thermistor string was not checked in FY 2020 due to challenges associated with COVID-19; but the string was checked in October of 2020. Units are set to log at least every half hour, providing data describing lake stratification at the sub-daily time scale. A similar thermistor string was placed in the same location in August of 2011. Data from this deployment are available through mid-December of 2014 at which time the thermistor string was lost.

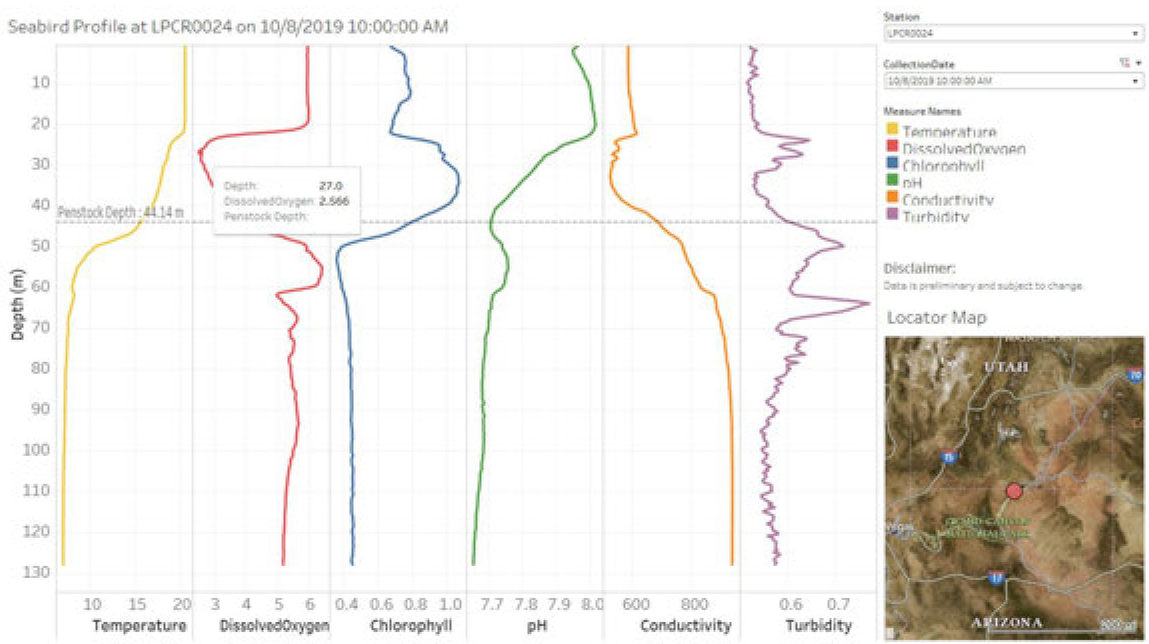

Figure 1. Example of a vertical water quality profile data visualization from the Lake Powell Water Quality Database. The interactive web-based Tableau interface allows the user to select a site and collection date from the drop-down lists on the upper right of the visualization panel and displays associated water quality data. A locator map shows the geographic position of the selected long-term sampling station. This example shows a profile from the Wahweap sampling station during the metalimnion low dissolved oxygen event that occurred in the fall of 2019.

Science Questions Addressed & Results

Historical nutrient data from the Lake Powell Water Quality Monitoring program are being used together with data from the four major gaged tributary sites to Lake Powell (USGS stream gages at Colorado River near Cisco, UT, 09180500; Green River at Green River, UT, 09315000; San Rafael River near Green River, UT, 09328500; and San Juan River near Bluff, UT, 09379500) and the gaged outflow site at Lees Ferry (USGS stream gage 09380000) to improve our understanding of the controls on phosphorus transport in the reservoir and links between phosphorus and food web dynamics in the Glen Canyon reach of the Colorado River. The goal of this analysis is to better understand the controls on phosphorus concentrations in releases from GCD with the eventual goal of modeling/predicting these concentrations.

Work is also ongoing to ensure that nutrient collection and analysis protocols are yielding the highest quality data possible, especially with regards to phosphorus species. Total dissolved phosphorus was added to the list of nutrient analyses in October of 2017. An inter-lab comparison of total phosphorus and soluble reactive phosphorus (SRP) concentrations was conducted in March of 2018. Currently, all nutrient and major ion analyses are done by Reclamation's Lower Colorado Region Water and Soil Laboratory in Boulder City, Nevada.

This lab was compared to the High Sierra Water Lab in Tahoe City, CA (High Sierra)—a lab that specializes in low detection phosphorus analysis. Dissolved phosphorus concentrations from the reservoir reported by High Sierra were, on average, 65% of the values reported by the Reclamation lab. Similarly, water column total phosphorus concentrations reported by High Sierra were, on average, 52% of the values reported by Reclamation. Samples were well above reported detection limits (at least 3x higher) in all cases. In contrast, High Sierra reported higher total phosphorus concentrations in reservoir inflow waters (where total suspended solids are high), averaging 2.1 times the concentrations reported by the Reclamation lab. The Reclamation lab has been very willing to re-run sample sets when the coefficient of variation on replicate samples is poor, and to troubleshoot anomalous readings. That said, any future work that focuses specifically on phosphorus cycling may benefit from consulting a lab like High Sierra that specializes in phosphorus measurements. Currently, funding to send duplicate samples for phosphorus measurements is beyond the program budget (full suite of phosphorus analytes would total $75 per sample at a lab like High Sierra).

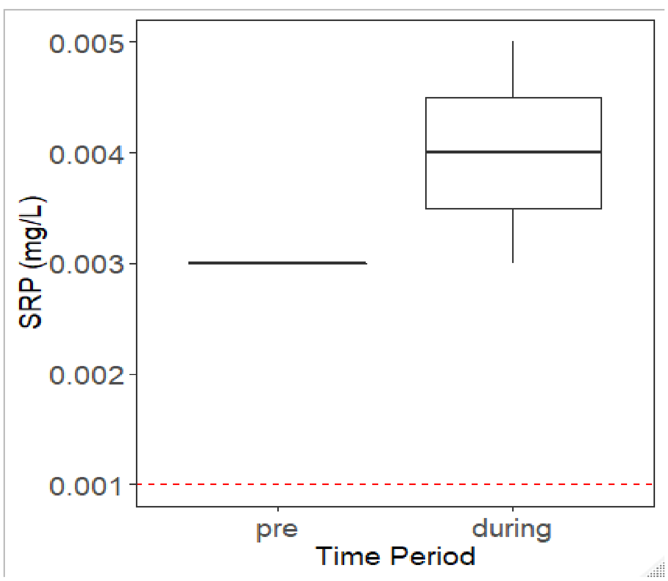

Figure 2. Soluble reactive phosphorus (SRP) concentrations (mg P L^{-1}) at Lees Ferry prior to and during the 2018 high-flow experiment (n=4 for the “pre” time period and n=3 for the “during” time period). Because there were only 3 samples taken from Lees Ferry during the high-flow experiment, the upper whisker represents one sample, the lower whisker represents the second sample, and the horizontal bar represents the third sample. The red dashed line indicates the method detection limit for SRP.

Water column stratification and outflow chemistry were monitored before, during, and after the fall 2018 High-Flow Experiment (HFE) to better understand the extent to which this experimental flow regime affects water quality and limnology. Water quality profiles and water samples were collected at the Wahweap station and water samples were collected at Lees Ferry before, during, and after the HFE. A transect of water quality profiles was also collected up-lake from Wahweap during the HFE. We saw very little change in water column stratification during the

HFE, but outflow chemistry was affected by the additional spill from the bypass tubes (which draw water from a lower depth). Some HFE related changes in outflow water quality have been explained elsewhere (Hueftle and Stevens, 2001), but sampling conducted during FY 2019 detected higher SRP at Lees Ferry during the HFE (Figure 2), an effect that could not be deciphered when detection limits for this analyte were higher. Additional regular sampling below the penstock depth at Wahweap began in May of 2018 and have continued through present. The sampling has revealed that SRP is often elevated approximately 10 m below the penstock relative to the penstock depth. This combined with the higher bottom water SRP concentrations generally observed at Wahweap indicates that SRP levels at the depth of the Jet Bypass tubes would generally be elevated as compared to the penstock depth. This suggests that the elevated SRP we observed in Lees Ferry during the 2018 HFE would likely hold for other high flow events (although the relative magnitude of the SRP increase would vary).

Finally, historical major ion data from Lees Ferry (USGS stream gage 09380000), and the three major gaged tributary sites to Lake Powell (USGS stream gages 09180500, 09315000, and 09379500) were used together with data from this monitoring program to examine patterns in salinity transport within the basin. Results show that Lake Powell acts as a sink for total dissolved solids, mainly via calcite precipitation. In addition, the reservoir functions to moderate downstream salt concentrations (Figure 3). These findings are contained in a manuscript published this year in the journal Limnology and Oceanography (Deemer and others, 2020).

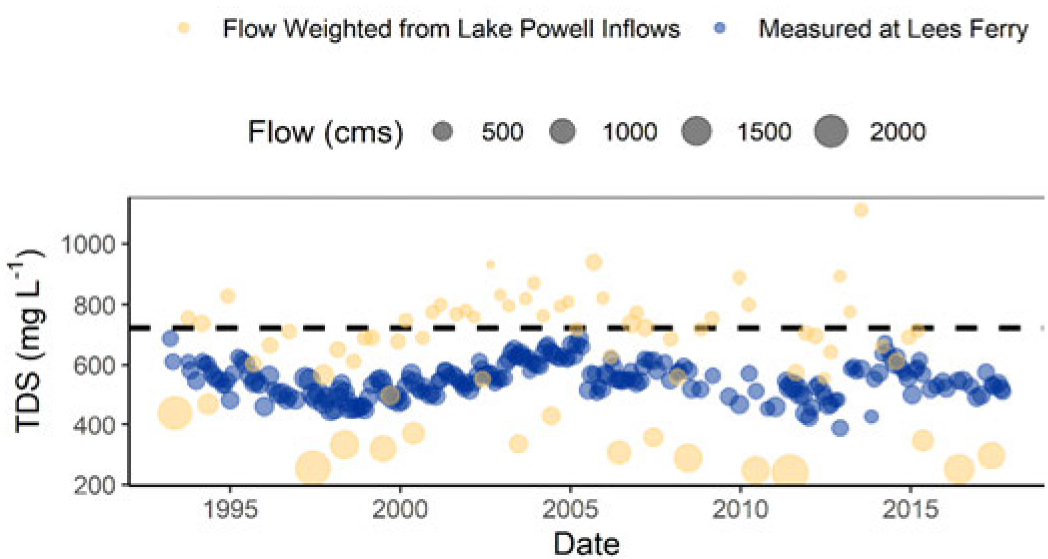

Figure 3. Measured total dissolved solids (TDS) concentrations at Lees Ferry (dark blue, n=223) versus discharge-weighted modeled salinity concentrations from the Colorado River and San Juan River inflow sites (light orange, n=71). TDS is calculated as the sum of the major ions Ca2+, Mg2+, Na+, K+, CO32-, HCO3-, Cl-, and SO42-. The size of each point is scaled to the discharge in cubic meters per second. The largest inflows for water supply generally occur in the months of May and June due to spring snowmelt. The dashed horizontal line represents the TDS limit at Hoover Dam (723 mg L-1). Adapted from Deemer and others, 2020.

Current Conditions

Hydrology

Lake Powell received 5.8 million acre feet (maf, 54% of the 1981-2010 average) of unregulated inflow in water year (WY) 2020. In comparison, inflow observed in WY 2019 was 12.8 maf (120% of average). The peak reservoir elevation in WY 2020 was 3615.28 feet on October 1, 2019 compared to an August peak of 3621.68 feet in WY 2019. At the end of WY 2020, Lake Powell's surface elevation was 3595.98 feet (104 feet from full pool) with a storage of 11.3 maf, or 46% of full capacity. This is down from the end of WY 2019 when surface elevation was 3615 ft and storage was 13.3 maf. Releases for WY 2020 totaled 8.23 maf (as opposed to 9.0 maf for WY 2018 and WY 2019) with operations under the Upper-Elevation Balancing Tier. Operations for WY 2021 will also fall under the Upper Elevation Balancing Tier, with a total projected annual release volume of 8.23 maf and an April 2021 adjustment to balancing releases projected.

Glen Canyon Dam Release Temperature

In late September and early October 2020, Glen Canyon Dam release temperatures briefly peaked at 13.1 °C, but generally remained below 12.5 ° C. Glen Canyon Dam release temperatures had reached a maximum of 16.1 °C by mid-October of 2019, which is a few degrees higher than the peak of 13 °C in October of 2018. These high temperatures are consistent with a recent trend wherein peak temperatures in GCD releases have exceeded 15 °C in 3 of the 6 previous years.

Lake Powell Limnology

In FY 2019, an interflow plume of low dissolved oxygen (DO) water moved through Lake Powell and contributed to historically low concentrations of DO in the GCD tailwaters (minimum DO of 4.0 mg/L in October of 2019, compared to 4.4 mg/L in October 2014 and 3.5 mg/L in 2005). The 2005 low DO event coincided with much lower recruitment and growth in the Glen Canyon rainbow trout fishery (Korman and others, 2012), so the low DO observed in Glen Canyon is of concern. COVID-19 related limitations in FY 2020 monitoring limited our capacity to predict a similar low DO event. Instead, in situ measurements from a subset of normal monitoring stations were compared to the same measurements in FY 2019 to determine there was low risk for another low DO event in October of 2020. Many of the low DO events have occurred during years where reservoir elevation is low and spring inflow is high, conditions that were not met in 2020. The minimum DO recorded by late October 2020 was well above fall 2019 concentrations at 6 mg/L. The National Park Service continues to track and monitor the quagga mussel population throughout Lake Powell, mainly by estimating veliger densities in zooplankton tows.

Program Support

A five-year agreement for continued support of the Lake Powell Water Quality Monitoring program was developed with Reclamation in FY 2018 (R18PG00108 - Water Quality Monitoring of Lake Powell). The agreement provides funding for GCMRC involvement in the program over the next year with the potential for funding for up to five years (January 1, 2018 - December 31, 2022). Projected budgets provide funding for a postdoctoral research ecologist ½ time and two research hydrologists at ¼ time. The agreement also projects support for 12 pay periods of IT specialist/geographer time for improvements to the Lake Powell water quality database and to develop a method of serving the data.

Research Collaboration Activities

Collaboration with Dickinson College has supported an analysis of the historical phytoplankton and zooplankton data described in Vernieu, 2015a. Initial findings show that phytoplankton biomass in the surface waters at Wahweap has increased significantly from 1993 to 2014 in all months but January. In contrast, zooplankton biomass shows only small genera-specific increases in February (rotifers) and June (*Cladocerans*) over the same time period. Of potential management interest is the increasing biovolume and temporal occurrence of Cyanobacteria, a phenomenon which may uncouple trophic interactions as well as negatively impacting lake recreation. These increases in phytoplankton biomass do not appear directly related to trends in water temperature. Based on a longer-term record of surface water temperatures starting in the mid-1960s, however, Wahweap surface waters are experiencing significant warming trends in winter, spring, and early summer (0.26, 0.59, and 0.24 °C per decade respectively via Sen slope analysis). Spring warming was nearly double the global average lake surface warming rate of 0.34 °C per decade reported by O'Reilly and others (2015). We plan to follow up on these findings by working with the Dickinson collaborator, Dr. Kristin Strock, to write up findings in a manuscript for submission at a peer reviewed scientific journal in FY 2021.

Collaboration with the Environmental Protection Agency supported floating chamber-based measurements of carbon dioxide and methane emissions in July of 2017 as part of a quarterly survey. We have compared the results of this single-time point survey to several global scale models that represent our current best estimate of the potential magnitude of greenhouse gas emissions from Lake Powell. This work is of interest given the recent inclusion of reservoirs in the IPCC flooded lands methodology (Lovelock and others, 2019) combined with both the large surface areas of Lake Powell and the general lack of data from arid region reservoirs. With the exception of one model, the estimated hydropower emissions for Lake Powell ranged from 10-32 kg CO_2-eq MWh^{-1}, compared to ~400-1000 kg CO_2-eq MWh^{-1} for natural gas, oil, and coal power plants. We also estimate that reduced littoral habitat under low water levels leads to ~50% reduction in the GHG equivalent emissions per MWh.

While emissions per MWh were low in Lake Powell as compared to other conventional energy sources (Figure 4), the sensitivity of GHG emissions to reservoir water levels may be an important policy consideration in the design and operation of other arid region systems with higher emissions. We are currently revising a manuscript for the Journal of Environmental Science and Policy that describes this effort.

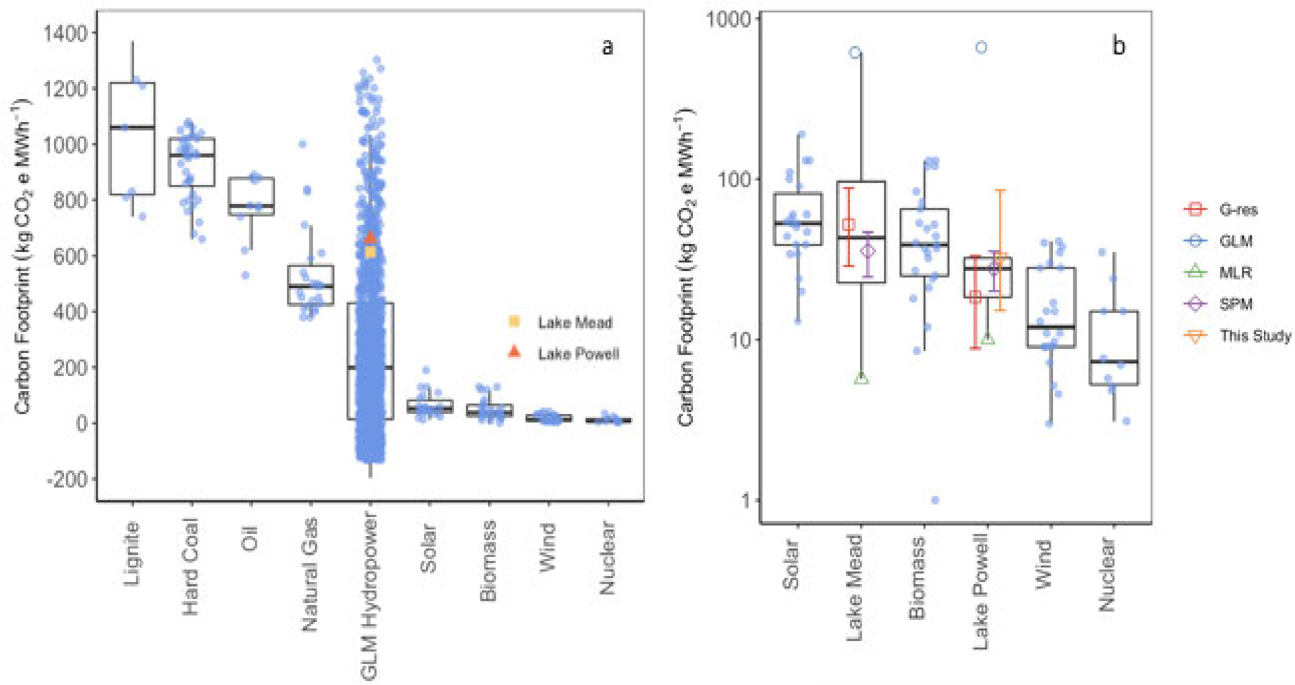

Figure 4. Panel a: Adaptation from Figure 2 of Scherer and Pfister (2016): Carbon footprints of various energy sources. The dots show all values included for each source (although only the 10th and 90th percentile of systems are shown for GLM hydropower to improve visualization). The boxes show upper and lower quartiles (25% and 75%), and the horizontal line indicates the median. The whiskers extend to the largest values no more than 1.5 * the IQR. Panel b: the renewable energy subset of panel a, plotted on a log scale and including the multiple carbon footprint estimates for Lake Powell and Lake Mead estimated by our modeling efforts. Color and shape of the marker indicates the source of the carbon footprint estimate for Lake Powell and Lake Mead. SPM refers to the surface productivity model (DelSontro and others, 2018), MLR refers to multiple linear regressions (Hertwich, 2013), GLM refers to generalized linear modeling (Scherer and Pfister, 2016), and G-res refers to the G-res too (Prairie and others, 2017). Whiskers indicate model or measurement 95% CI range.

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Budget

Lake Powell (NOT GCDAMP funded)

	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 21.733%	Total
Budgeted Amount	$147,187	$9,109	$10,951	$0	$0	$36,348	**$203,595**
Actual Spent	$128,607	$2,474	$9,526	$0	$0	$30,558	**$171,165**
(Over)/Under Budget	**$18,580**	**$6,635**	**$1,425**	**$0**	**$0**	**$5,790**	**$32,430**
FY19 Carryover	**$145,652**					**FY20 Carryover**	**$178,082**

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

- This project is funded entirely by Reclamation with **non-GCDAMP funding**.
- High carryover amounts from one fiscal year to another are an artifact of this project being budgeted on calendar years rather than fiscal years.

Appendix 2: Deliverables (Products), FY 2018 – FY 2020*

(*Note: In past Annual Reports, products were shown in a table format. This year they are shown in a list format, from newest to oldest.)

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

Presentations

2020

Dean, D.J., and Topping, D.J., 2020, Biogeomorphic feedbacks in the Southwestern USA—Exploring the mechanisms of geomorphic change and the effectiveness of mitigation measures—presentation, February 4-6, 2020, Grand Junction, Colo., RiversEdge West Riparian Restoration Conference.

2019

Camenen, B., Dramais, G., Le Coz, J., and Topping, D.J., 2019, Continuous sand-transport estimation on the Colorado River: Auckland, New Zealand, November 16-21, RCEM 2019, the 11th Symposium on River, Coastal, and Estuarine Morphodynamics.

Dean, D.J., and Topping, D.J., 2019, Geomorphic change and biogeomorphic feedbacks in a dryland river—The Little Colorado River, Arizona, USA: Geological Society of America Abstracts with Programs, v. 51, n. 5, https://doi.org/10.1130/abs/2019AM-339900.

Dean, D.J., and Topping, D.J., 2019, Geomorphic change, biogeomorphic feedbacks, and the downstream transformation of floodwaves in the Little Colorado River, Arizona, USA: Flagstaff, Ariz., 15th Biennial Conference of Science & Management on the Colorado Plateau and Southwest Region, September 9-12, 2019, High Country Conference Center, Northern Arizona University.

Grams, P.E., Buscombe, D., and Topping, D.J., 2019, Sediment budget uncertainty—Signal and noise in the sand budget of a river with episodic supply and transport: Auckland, New Zealand, November 16-21, RCEM 2019, the 11th Symposium on River, Coastal, and Estuarine Morphodynamics.

2018

Dean, D.J., and Topping, D.J., 2018, Geomorphic change and biogeomorphic feedbacks in the Little Colorado River, AZ, Geological Society of America Abstracts with Programs, v. 50, n. 5, https://doi.org/10.1130/abs/2018RM-313857.

Grams, P.E., Buscombe, D.D., Kaplinksi, M., and Topping, D.J., 2018, Patterns of riverbed sand-storage change on the Colorado River in Grand Canyon, Geological Society of America Abstracts with Programs, v. 50, n. 5, https://doi.org/10.1130/abs/2018RM-314193.

Topping, D.J., Griffiths, R.E., Rubin, D.M., Grams, P.E., Buscombe, D.D., Sabol, T.A., and Dean, D.J., 2018, Grain-size limitation of sand storage in the Colorado River in Grand Canyon National Park, Geological Society of America Abstracts with Programs, v. 50, n. 5, https://doi.org/10.1130/abs/2018RM-313931.

Topping, D.J., Rubin, D.M., Griffiths, R.E., Dean, D.J., Schmidt, J.C., Grams, P.E., Mueller, E.R., 2018, Grain-size controls on sand storage in rivers—presented abstract EP31C-2358: Washington, D.C., December10-14, AGU 2018 Fall Meeting.

2017

Dean, D.J., Diehl, R.M., and Topping, D.J., 2017, Biogeomorphic feedbacks in the Southwestern USA—Exploring the mechanisms of geomorphic change and the effectiveness of mitigation measures—presented abstract EP42A-01: New Orleans, LA, December 11-15, AGU 2017 Fall Meeting.

Grams, P.E., Buscombe, D., Topping, D.J., and Mueller, E.R., Identification of discontinuous sand pulses on the bed of the Colorado River in Grand Canyon—presented abstract EP41A-1825: New Orleans, LA, December 11-15, AGU 2017 Fall Meeting.

Topping, D.J., Griffiths, R.E., Dean, D.J., Grams, P.E., Buscombe, D.D., and Mueller, E.R., 2017, On-demand continuous mass-balance sediment budgets for river science and management: Geological Society of America Abstracts with Programs, v. 49, n. 6, https://doi.org/10.1130/abs/2017AM-297045. (Invited Presentation)

Journal Articles

2020

Rubin, D.M., Buscombe, D., Wright, S.A., Topping, D.J., Grams, P.E., Schmidt, J.C., Hazel, J.E., Kaplinski, M.A., and Tusso, R., 2020, Causes of variability in suspended-sand concentration evaluated using measurements in the Colorado River in Grand Canyon: Journal of Geophysical Research: Earth Surface, v. 125, no. 9, p. 1-23 p., https://doi.org/10.1029/2019JF005226.

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

2019

Dean, D.J., and Topping, D.J., 2019, Geomorphic change and biogeomorphic feedbacks in a dryland river: The Little Colorado River, Arizona, USA: Geological Society of America Bulletin, v. 131, p. 1920-1942, with additional supporting material in the Geological Society of America Data Repository, https://doi.org/10.1130/B35047.1.

Grams, P.E., Buscombe, D., Topping, D.J., Kaplinski, M., 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, p. 160-178, https://doi.org/10.1002/esp.4489.

2018

Voichick, N., Topping, D.J., and Griffiths, R.E., 2018, Technical note—False low turbidity readings during high suspended-sediment concentrations: Hydrology and Earth System Sciences, v. 22, p. 1767-1773, https://doi.org/10.5194/hess-22-1767-2018.

2017

Griffiths, R.E., and Topping, D.J., 2017, Importance of measuring discharge and sediment transport in lesser tributaries when closing sediment budgets: Geomorphology, v. 296, p. 59-73, https://doi.org/10.1016/j.geomorph.2017.08.037.

USGS Reports

2020

Sabol, T.A., Griffiths, R.E., Topping, D.J., Mueller, E.R., Tusso, R.B., and Hazel, J.E., Jr., *In press*, Strandlines from large floods in the Colorado River in Grand Canyon National Park: U.S. Geological Survey Scientific Investigations Report.

Unema, J.A., Topping, D.J., Kohl, K.A., Pillow, M.J., and Caster, J.J., *In press*, Historical floods and geomorphic change in the lower Little Colorado River during the late 19th to early 21st centuries: U.S. Geological Survey Scientific Investigations Report.

USGS Data Releases

2019

Dean, D.J., and Topping, D.J., 2019, Geomorphic change data for the Little Colorado River, AZ, USA: U.S. Geological Survey data release, https://doi.org/10.5066/P9XPWIBM.

Web Applications

2018-2020

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

Stage, discharge, sediment transport, water-quality, and sand-budget data are served through the USGS-GCMRC website. A 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. Updated every day to month depending on data type: http://www.gcmrc.gov/discharge_qw_sediment/.

Project B Deliverables: Sandbar and Sediment Storage Monitoring and Research

Presentations

2020

Grams, P.E., 2020, Project B: Effects of dam releases on in-channel sediment storage and sandbar dynamics—presentation to the GCDAMP Annual Reporting Meeting: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, January 13, 2020, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-ProjectBEffectsDamReleaseSedimentStorageSandbarDynamics-Presentation-508-UCRO.pdf.

Grams, P.E., and Topping, D.J., 2020, Evaluating the frequency of triggered spring High-Flow Experiments (HFE's) assumed in the Long-Term Experimental and Management Plan (Project B.1)—presentation to the GCDAMP Technical Working Group: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, June 24, 2020, https://www.usbr.gov/uc/progact/amp/twg/2020-06-24-twg-meeting/20200624-Grams-TWG.pdf.

Hazel, J., Kaplinski, M., Grams, P.E., and Tusso, R., 2020, Changes in sandbars and campsites during the HFE protocol (Project B.1)—presentation to the GCDAMP Annual Reporting Meeting: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, January 13, 2020: https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-ChangesSandbarsCampsitesDuringHFEProtocol-Presentation-508-UCRO.pdf.

Mueller, E. and Grams, P.E., 2020, Using a simple physical model to evaluate sandbar dynamics in Grand Canyon—presentation: Provo, Utah, May 4-5, 2020, Geological Society of America, Rocky Mountain Section Meeting. (Project B.1: Talk on sandbar modeling)

2019

Grams, P.E., Buscombe, D., Topping, D.J., 2019, Sediment budget uncertainty—Signal and noise in the sand budget of a river with episodic supply and transport, *in* Friedrich, H. and Bryan, K. eds., Auckland, New Zealand, November 16-21, RCEM 2019, The 11th Symposium on River, Coastal, and Estuarine Morphodynamics. (Project B.2: Presentation on the sediment budget)

Guala, M., Heisel M., Musa M., Singh A., Buscombe D., Grams, P.E., 2019, A mixed scaling model for migrating bedform velocities in sand bedded rivers: San Francisco, Calif., December 9-13, 2019, American Geophysical Union Annual Meeting. (Project B.2: Presentation on bedload sand transport)

Lima, R., Buscombe, D., Sankey, T., Grams, P., & Mueller, E., 2019, Using oblique imagery to measure hypsometric changes in sandbar volume following controlled floods in the Grand Canyon: Reno, Nevada, June 24-28, 2019, SEDHYD 2019, https://www.sedhyd.org/2019/proceedings/SEDHYD_Proceedings_2019_Volume5.pdf. (Project B.1: Proceedings paper on remote camera image processing)

Journal Articles

2020

Ashley, T.C., McElroy, B., Buscombe, D., Grams, P.E., and Kaplinski, M., 2020, Estimating bedload from suspended load and water discharge in sand bed rivers: Water Resources Research, v. 56, no. 2, e2019WR025883, p. 1-25, https://doi.org/10.1029/2019WR025883. (Project B.2: Journal article on bedload sand transport)

Butterfield, B.J., Grams, P.E., Durning, L.E., Hazel, J.E., Palmquist, E.C., Ralston, B.E., and Sankey, J.B., 2020, Associations between riparian plant morphological guilds and fluvial sediment dynamics along the regulated Colorado River in Grand Canyon: River Research and Applications, v. 36, no. 3, p. 410-421, https://doi.org/10.1002/rra.3589. (Project B.1 Journal article on sandbars and riparian vegetation)

Chapman, K.A., Best, R.J., Smith, M.E., Mueller, E.R., Grams, P.E., and Parnell, R.A., 2020, Estimating the contribution of tributary sand inputs to controlled flood deposits for sandbar restoration using elemental tracers, Colorado River, Grand Canyon National Park, Arizona: GSA Bulletin, online, https://doi.org/10.1130/B35642.1. (Project B.1: Journal article on source of sand for HFEs)

Guala, M., Heisel, M., Singh, A., Musa, M., Buscombe, D., and Grams, P., 2020, A mixed length scale model for migrating fluvial bedforms: Geophysical Research Letters, v. 47, no. 15, p. 1-10, https://doi.org/10.1029/2019GL086625. (Project B.2: Journal article on bedload sand transport)

Rubin, D.M., Buscombe, D., Wright, S.A., Topping, D.J., Grams, P.E., Schmidt, J.C., Hazel, J.E., Kaplinski, M.A., and Tusso, R., 2020, Causes of variability in suspended-sand concentration evaluated using measurements in the Colorado River in Grand Canyon: JGR Earth Surface, v. 125, no. 9, e2019JF005226, p. 1-23, https://doi.org/10.1029/2019JF005226. (Project B.2: Journal article on suspended sand transport)

2019

Buscombe, D., 2019, SediNet—A configurable deep learning model for mixed qualitative and quantitative optical granulometry: Earth Surface Processes and Landforms, v. 45, no. 638-651, https://doi.org/10.1002/esp.4760. (Project B.2: Journal article on methods for measuring sediment grain size from images)

Leary, K.C.P., and Buscombe, D., 2019, Estimating sand bedload in rivers by tracking dunes—A comparison of methods based on bed elevation time-series—preprint discussion paper: Earth Surface Dynamics, v. 8, no. 1, p. 161–172, https://doi.org/10.5194/esurf-8-161-2020. (Project B.2: Journal article on methods for measuring sand bedload transport)

2018

Buscombe, D., and Grams, P.E., 2018, Probabilistic substrate classification with multispectral acoustic backscatter—A comparison of discriminative and generative models: Geosciences, v. 8, no. 11, article 395, https://doi.org/10.3390/geosciences8110395. (Project B.2 Journal article on automated methods for substrate classification)

Buscombe, D., and Ritchie, A.C., 2018, Landscape classification with deep neural networks: Geosciences, v. 8, no. 7, article 244, https://doi.org/10.3390/geosciences8070244. (Project B.2 Journal article on automated methods for image classification)

Hadley, D.R., Grams, P.E., and Kaplinski, M.A., 2018, Quantifying geomorphic and vegetation change at sandbar campsites in response to flow regulation and controlled floods, Grand Canyon National Park, Arizona: River Research and Applications, v. 34, no. 9, p. 1208-1218, https://doi.org/10.1002/rra.3349. (Project B.1 Journal article on causes of campsite area change)

Hamill, D., Buscombe, D., and Wheaton, J.M., 2018, Alluvial substrate mapping by automated texture segmentation of recreational-grade side scan sonar imagery: PLOS One, v. 13, no. 3, e0194373, p. 1-28, https://doi.org/10.1371/journal.pone.0194373. (Project B.2 Journal article on automated methods for substrate classification)

Grams, P.E., Buscombe, D., Topping, D.J., Kaplinski, M.A., and Hazel, J.E., Jr., 2018, How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise: Earth Surface Processes and Landforms, v. 44, no. 1, p. 160-178, https://doi.org/10.1002/esp.4489. (Project B.2 Journal article on long-term monitoring of sand storage)

Kasprak, A., Sankey, J.B., Buscombe, D., Caster, J., East, A.E., and Grams, P.E., 2018, Quantifying and forecasting changes in the areal extent of river valley sediment in response to altered hydrology and land cover: Progress in Physical Geography: Earth and Environment, v. 42, no. 6, p. 739-764, https://doi.org/10.1177/0309133318795846. (Project B.1 Journal article on sand-area change)

Mueller, E.R., Grams, P.E., Hazel, J.E., Jr., and Schmidt, J.C., 2018, Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon: Sedimentary Geology, v. 363, p. 181-199, https://doi.org/10.1016/j.sedgeo.2017.11.007. (Project B.1 Journal article on sandbar changes)

USGS Reports

2018

Grams, P.E., Tusso, R.B., and Buscombe, D., 2018, Automated remote cameras for monitoring alluvial sandbars on the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 2018-1019, 50 p., https://doi.org/10.3133/ofr20181019. (Project B.1 Report on use of remote camera images for sandbar monitoring)

Hadley, D. R., Grams, P. E., Kaplinski, M. A., Hazel, J.E., J., & Parnell, R. A., 2018, Geomorphology and vegetation change at Colorado River campsites, Marble and Grand Canyons, Arizona: U.S. Geological Survey Scientific Investigations Report 2017–5096, 64 p., https://doi.org/10.3133/sir20175096. (Project B.1 Report on causes of campsite area change)

Extended Abstracts, Conference Proceedings

2019

Grams, P.E., 2019, Sandbar deposition caused by high-flow experiments on the Colorado River downstream from Glen Canyon Dam—November 2012-November 2018, *in* High-flow experiments assessment extended abstracts—Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting Presentations, March 12-13, 2019: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, p. 12-22, https://www.usbr.gov/uc/progact/amp/amwg/2019-03-06-amwg-meeting/20190301-HFE_Extended_Abstracts-Combined_FINAL.pdf. (Project B.1: Extended abstract on the effects of HFEs on sandbars)

Topping, D.J., Grams, P.E., Griffiths, R.E., Hazel, J.E., Kaplinski, M.A., Dean, D.J., Voichick, N., Unema, J.A., and Sabol, T.A., 2019, Optimal timing of high-flow experiments for sandbar deposition, *in* High-flow experiments assessment extended abstracts—Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting presentations, March 12-13, 2019, Phoenix, Ariz.: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, p. 3-9, https://www.usbr.gov/uc/progact/amp/amwg/2019-03-06-amwg-meeting/20190301-HFE_Extended_Abstracts-Combined_FINAL.pdf. (Project B.1: Extended abstract on the effects of HFEs on sandbars)

2018

Buscombe, D., Grams, P.E., & Kaplinski, M., 2018, Probabilistic models of seafloor composition using multispectral acoustic backscatter: GeoHab 2018 International Symposium, R2Sonic Multispectral Backscatter competition entry. Download using online form at: https://www.r2sonic.com/geohab2018/. (Project B.2 Report on automated methods for substrate classification)

USGS Data Releases

2020

Chapman, K.A., Best, R.J., Smith, M.E., Mueller, E.R., Grams, P.E., and Parnell, R.A., 2020, Tributary sand input data, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9C0IN56. (Project B.1: Data release on source of sand for HFEs)

Grams, P.E., Hazel, J.E., Jr., Kaplinski, M., Ross, R.P., Hamill, D., Hensleigh, J., and Gushue, T., 2020, Long-term sandbar monitoring data along the Colorado River in Marble and Grand Canyons, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P93F8JJK.

Tusso, R.B., Rubin, D.M., Buscombe, D., Hazel Jr., J.E., Topping, D.J., and Grams, P.E., 2020, Measurements of bed grain size on the Colorado River in Grand Canyon National Park, Arizona—2000 to 2014: U.S. Geological Survey data release, https://doi.org/10.5066/P92Y65R8. (Project B.2 Bed sediment grain size data release)

2018

Buscombe, D.D., Grams, P.E., and Kaplinski, M.A., 2018, Acoustic backscatter—Data & Python code: U.S. Geological Survey data release, https://doi.org/10.5066/F7B56HM0. (Project B.2 Computer code automated methods for substrate classification)

Hadley, D.R., Kaplinski, M.A., Hazel, J.E., Jr., Gushue, T.M., Ross, R.P., Grams, P.E., Parnell, R.A., and Fairley, H.C., 2018, Geomorphology and campsite data, Colorado River, Marble and Grand Canyons, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/F7FJ2FQQ. (Project B.1 Data on causes of campsite area change)

Kasprak, A., Sankey, J.B., Buscombe, D.D., Caster, J., East, A.E, Grams, P.E, 2018, River valley sediment connectivity data, Colorado River, Grand Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9SX3MGY. (Project B.1 data on sand-area change)

Sankey, J.B., Chain, G.R., Solazzo, D., Durning, L.E., Bedford, A., Grams, P.E., and Ross, R.P., 2018, Sand classifications along the Colorado River in Grand Canyon derived from 2002, 2009, and 2013 high-resolution multispectral airborne imagery: U.S. Geological Survey data release, https://doi.org/10.5066/P99TN424. (Project B.1 data on sand-area change)

USGS Data

2018-2020

Project B.1: Data from long-term sandbar monitoring sites – Website: www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/

Project B.2: Glen Canyon Channel Mapping Data –Presented at annual reporting meeting and https://grandcanyon.usgs.gov/portal/home/

USGS Photos

2018-2020

Project B.1: Images from remote camera monitoring of sandbars – Website: www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/

GCRG Photos

2018-2020

Project B.1: Images from GCRG Adopt-a-Beach program – Website: www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/

Project C Deliverables: Riparian Vegetation Monitoring and Research

Presentations

2020

Butterfield, B.J. and Palmquist, E.C., 2020, Veg-Sand Feedbacks and Updates on Project C.1 and C.3—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, AZ, January 14, 2020: U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Butterfield, B.J., Palmquist, E.C., Ralston, B.E., 2020, Status and Trends of Riparian Vegetation: 2014-2019—poster presentation at the GCDAMP Annual Reporting Meeting: Phoenix, AZ, January 13, 2020: U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Durning, L., Sankey, J.B., Sankey, T.T., Butterfield, B., Grams, P., Gushue, T., 2020. Species-level evaluation of riparian vegetation dynamics using remotely sensed imagery from aerial overflights—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, AZ, January 13, 2020: U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Palmquist, E.C., Allan, G.A., Ogle, K., Whitham, T., Butterfield, B., Shafroth, P., 2020, Genetic structure and gene flow in Grand Canyon riparian plants—Implications for vegetation management—poster presentation at the GCDAMP Annual Reporting Meeting: Phoenix, AZ, January 13, 2020: U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Palmquist, E.C., Ogle, K., Butterfield, B.J., 2020, Provenance of a woody riparian species changes traits but not flood response under a common climatic setting—virtual presentation: August 3-6, 2020, Ecological Society of America 2020 Annual Meeting, https://www.esa.org/saltlake/.

2019

Bedford, A., Sankey, T.T., Sankey, J.B., Durning, L., Ralston, B.E., 2019, Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA—poster at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Bedford, A., Sankey, T.T., Sankey, J.B., Durning, L., Ralston, B.E., 2019, Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA—presentation: Flagstaff, Ariz., September 9-12, 2019, 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region.

Butterfield, B.J., Sankey, J.B., Palmquist, E.C., Durning, L., 2019, Effects of HFEs on sandbar vegetation, Grand Canyon, Arizona—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Butterfield, B.J., Sankey, J.B., Palmquist, E.C., Durning, L., 2019, Riparian vegetation monitoring and research, Grand Canyon, Arizona—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Durning, L., Sankey, J.B., 2019, Landscape scale riparian corridor analysis using 2013 remotely sensed airborne data, Grand Canyon, Arizona—poster presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Palmquist, E.C., Allan, G.A., Ogle, K., Whitham, T., Butterfield, B., Shafroth, P., 2019, Genetic structure and gene flow in woody riparian plants—A case study in the Grand Canyon—presentation: Flagstaff, Ariz., September 9-12, 2019, 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region.

Palmquist, E.C., Allan, G.A., Ogle, K., Whitham, T., Butterfield, B., Shafroth, P., 2019, Genetic structure and gene flow in woody riparian plants—Implications for restoration in the Grand Canyon—presentation: Phoenix, Ariz., February 5-7, 2019, RiversEdge West Riparian Restoration Conference.

Palmquist, E.C., Hazelton, A., Butterfield, B.J., Ralston, B.E., 2019, Ground-based riparian vegetation monitoring and research—poster presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Sankey, T.T., Bedford, A., Sankey, J.B., Ralston, B., and Durning, L., 2019, Remote sensing of tamarisk and tamarisk beetle (*Diorhaba carinulata*) impacts along the Colorado River in Grand Canyon National Park and Glen Canyon National Recreation Area—presentation: Phoenix, Ariz. February 5-7, 2019, RiversEdge West Riparian Restoration Conference.

2018

Butterfield, B.J., Palmquist, E.C., and Ralston, B.E., 2018, Hydrological regime and climate interactively shape riparian vegetation composition along the Colorado River, Grand Canyon—poster presentation: Bozeman, Mont., July 22-27, 2018, Natural Ecosystems as Benchmarks for Vegetation Science, International Association of Vegetation Scientists 61st Annual Symposium.

Butterfield, B.J., Sankey, J.B., Palmquist, E.C., Durning, L., 2018, Riparian vegetation monitoring and research in the Colorado River Ecosystem—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 6, 2018, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Durning, L, Sankey, J.B., 2018, Landscape scale riparian vegetation mapping and analysis using remotely sensed data—poster at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 6, 2018, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Kasprak, A., Sankey, J.B., Buscombe, D., Caster, J., Durning, L.E., East, A.E., and Grams, P., 2018, Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the Colorado River in Grand Canyon—presentation: Washington, D.C., December 10-14, 2018, American Geophysical Union Fall Meeting.

Sterner, S., Palmquist, E.C., Ralston, B.E., Butterfield, B.J., 2018, Ground-based riparian vegetation monitoring and research—poster presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 6, 2018, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

2017

Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Relating riparian vegetation, the Colorado River, climate, and resource management via remote sensing in Grand Canyon: Flagstaff, Ariz., November 6, 2017, Northern Arizona University, Biology Department Seminar.

Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Riparian remote sensing in Glen and Grand Canyons—Vegetation, sediment, and cultural resources—presentation: Boulder City, Nev., November 15th, 2017, Colorado River Steering Committee, Face to Face Meeting, Lower Colorado Region Regional Training Center.

Journal Articles

2020

Butterfield, B.J., Grams, P.E., Durning, L.E., Hazel, J.E., Palmquist, E.C., and Ralston, B.E., 2020, Associations between riparian plant morphological guilds and fluvial sediment dynamics along the regulated Colorado River in Grand Canyon: River Research and Applications, v. 36, no. 3, p. 410-421, https://doi.org/10.1002/rra.3589.

Kasprak, A., Sankey, J.B., Butterfield, B., *2020, In press*, Future regulated flows of the Colorado River in Grand Canyon foretell decreased areal extent of sediment and increases in riparian vegetation: Environmental Research Letters.

2019

Palmquist, E.C., Sterner, S.A., and Ralston, B.E., 2019, A comparison of riparian vegetation sampling methods along a large, regulated river: River Research and Applications, v. 35, no. 6, p. 759-767, https://doi.org/10.1002/rra.3440.

2018

Bedford, A., Sankey, T.T., Sankey, J.B., Durning, L.E., and Ralston, B.E., 2018, Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA: Ecological Indicators, v. 89, p. 365-375, https://doi.org/10.1016/j.ecolind.2018.02.026.

Butterfield, B.J., Palmquist, E.C., and Ralston, B.E., 2018, Hydrological regime and climate interactively shape riparian vegetation composition along the Colorado River, Grand Canyon: Applied Vegetation Science, v. 21, no. 4, p. 572-583, https://doi.org/10.1111/avsc.12390.

Palmquist, E.C., Ralston, B.E., Merritt, D.M., and Shafroth, P.B., 2018, Landscape-scale processes influence riparian plant composition along a regulated river: Journal of Arid Environments, v. 148, p. 54-64, https://doi.org/10.1016/j.jaridenv.2017.10.001.

USGS Reports

2018

Palmquist, E.C., Ralston, B.E., Sarr, D.A., and Johnson, T.C., 2018, Monitoring riparian-vegetation composition and cover along the Colorado River downstream of Glen Canyon Dam, Arizona: U.S. Geological Survey Techniques and Methods, book 2, chap. A14, 65 p., https://doi.org/10.3133/tm2A14.

USGS Data Releases

2020

Kasprak, A., Sankey, J.B., Butterfield, B., *2020, In production*, Future regulated flows of the Colorado River in Grand Canyon foretell decreased areal extent of sediment and increases in riparian vegetation: U.S. Geological Survey data release.

2018

Durning, L.E., Sankey, J.B., Bedford, A., and Sankey, T.T., 2018, Riparian species vegetation classification data for the Colorado River within Grand Canyon derived from 2013 airborne imagery: U.S. Geological Survey data release, https://doi.org/10.5066/P9OUB1RS.

Palmquist, E.C., 2018, Climate, hydrology and riparian vegetation composition data, Grand Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/F7DN4493.

Sankey, J.B., Chain, G.R., Solazzo, D., Durning, L.E., Bedford, A., Grams, P.E., and Ross, R.P., 2018, Sand classifications along the Colorado River in Grand Canyon derived from 2002, 2009, and 2013 high-resolution multispectral airborne imagery: U.S. Geological Survey data release, https://doi.org/10.5066/P99TN424.

2017

Palmquist, E.C, 2017, Riparian vegetation and environmental variables, Colorado River, 2014—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7V986X3.

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

Presentations

2020

Sankey, J.B., Caster, J.C., Fairley, H., 2020, Effects of dam operations and vegetation management for archaeological sites along the Colorado River in Grand Canyon—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., January 29, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

2019

Caster, J, Sankey, J.B., Kasprak, A., Fairley, H., East, A., 2019, Process and progress in monitoring surficial changes to archaeological sites within Grand Canyon river corridor—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Fairley, H.C., 2019, Understanding dam effects on downstream archaeological resources—Lessons learned from three decades of research downstream from Glen Canyon Dam, Arizona—presentation: Albuquerque, New Mex., April 11, 2019, Society for American Archaeology Annual Meeting.

Fairley, H., Sankey, J., Caster, J., East, A., Kasprak, A., Collins, B., Corbett, S., 2019, "Wind (and sand) in the willows"—Exploring the relationship between dam-regulated flows, sediment supply, vegetation encroachment, and archaeological site preservation in Glen and Grand Canyons, Arizona—presentation: Marble Canyon, Ariz., March 29, 2019, Grand Canyon River Guides Training Seminar.

Kasprak, A., Sankey, J.B., Buscombe, D., Durning, L., Caster, J., Grams, P., East, A., Butterfield, B., 2019, Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the Colorado River in Grand Canyon: Washington, D.C., December 1-14, 2018, AGU Fall Meeting.

Sankey, J.B., Caster, J, Kasprak, A., East, A., Fairley, H., 2019, The response of source-bordering aeolian dunefields to the 2012-2016 High-Flow Experiments of the Colorado River in Grand Canyon—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., March 13, 2019, High-Flow Experiment Workshop, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

2018

Fairley, H., Sankey, J., East, A., Caster, J., and Kasprak, A., 2018, Beyond compliance—Evolution and design of a program to monitor downstream dam effects at archaeological sites in Glen and Grand Canyons, Arizona—presentation: Flagstaff, Ariz., August 8-12, 2018, Pecos Conference of Southwestern Archaeology.

Kasprak, A., Sankey, J.B., Buscombe, D., Durning, L., Caster, J., Grams, P., East, A., Butterfield, B., 2018, Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the Colorado River in Grand Canyon—presentation: Washington, D.C., December 1-14, 2018 Fall AGU Meeting, Abstract EP33B-04, https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/394299.

Sankey, J.B., Kapsrak, A., Caster, J., Sankey, T., Andrews, T., Solazzo, D., 2018, Integrating lidar and SfM data from ground-based, unmanned (UAV) and manned aerial platforms to estimate sediment budgets for aeolian dunefields—presentation: Washington, D.C., December 1-14, 2018, AGU Fall Meeting.

2017

Kasprak, A., Bransky, N., Caster, J., Sankey, J.B., and Sankey, T.T., 2017, The effect of topographic survey technique and resolution on the interpretation of geomorphic change in river valleys—presentation: New Orleans, LA, December 11-15, 2017, AGU Fall Meeting, Abstract EP31D-0379, https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/221737.

Sankey, J.B., Kasprak, A., Caster, J., and East, A.E., 2017, Inferring the effects of sediment supply changes on sediment connectivity from river-valley morphodynamics—presentation: New Orleans, LA, December 11-15, 2017 AGU Fall Meeting, Abstract EP31A-0330, https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/242852.

Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Relating riparian vegetation, the Colorado River, climate, and resource management via remote sensing in Grand Canyon—presentation: Flagstaff, Ariz., November 6th, 2017, Northern Arizona University, Biology Department Seminar.

Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Riparian remote sensing in Glen and Grand Canyons—Vegetation, sediment, and cultural resources—presentation: Boulder City, Nev, November 15th, 2017, Colorado River Steering Committee, Face to Face Meeting, Lower Colorado Region Regional Training Center.

Journal Articles

2020

Kasprak, A., Sankey, J.B., and Butterfield, B.J., 2020, *in press*, Future regulated flows of the Colorado River in Grand Canyon foretell decreased areal extent of sediment and increases in riparian vegetation: Environmental Research Letters.

2019

Kasprak, A., Bransky, N.D., Sankey, J.B., Caster, J., and Sankey, T.T., 2019, The effects of topographic surveying technique and data resolution on the detection and interpretation of geomorphic change: Geomorphology, v. 333, p. 1-15, https://doi.org/10.1016/j.geomorph.2019.02.020.

2018

Kasprak, A., Sankey, J.B., Buscombe, D., Caster, J., East, A.E., and Grams, P.E., 2018, Quantifying and forecasting changes in the areal extent of river valley sediment in response to altered hydrology and land cover: Progress in Physical Geography: Earth and Environment, v. 42, no. 6, p. 739-764, https://doi.org/10.1177/0309133318795846.

Sankey, J.B., Caster, J.J., Kasprak, A., and East, A.E., 2018, The response of source-bordering aeolian dunefields to sediment-supply changes 2—Controlled floods of the Colorado River in Grand Canyon, Arizona, USA: Aeolian Research, v. 32, p. 154-169, https://doi.org/10.1016/j.aeolia.2018.02.004.

Sankey, J.B., Kasprak, A., Caster, J.J., East, A.E., and Fairley, H., 2018, The response of source-bordering aeolian dunefields to sediment-supply changes 1—Effects of wind variability and river-valley morphodynamics: Aeolian Research, v. 32, p. 228-245, https://doi.org/10.1016/j.aeolia.2018.02.005.

USGS Reports

2020

Caster, J., Sankey, J.B., Kasprak, A., Fairley, H., *In press,* 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: USGS Open-File Report.

2019

Cook, T., East, A.E., Fairley, H., and Sankey, J.B., 2019, Managing sand along the Colorado River to protect cultural sites downstream of Glen Canyon Dam: U.S. Geological Survey Fact Sheet 2019-3054, 6 p., https://doi.org/10.3133/fs20193054.

USGS Data Releases

2020

Kasprak, A., Sankey, J.B., Butterfield, B., *2020, In production*, Future regulated flows of the Colorado River in Grand Canyon foretell decreased areal extent of sediment and increases in riparian vegetation: U.S. Geological Survey data release.

2018

Caster, J.J., Sankey, J.B., and Fairley, H., 2018, Meteorological data for selected sites along the Colorado River corridor, Arizona, 2014-2015: U.S. Geological Survey data release, https://doi.org/10.5066/F7DZ0771.

Kasprak, A., Sankey, J.B., Buscombe, D.D., Caster, J., East, A.E, Grams, P.E, 2018, River valley sediment connectivity data, Colorado River, Grand Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9SX3MGY.

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

Presentations

2020

Dibble, K.L, 2020, Fish communities in the Colorado River ecosystem—Drivers, trends, and future uncertainties—presentation to the community: Moab, Utah: February 20, 2020, 'Future of Lake Powell' Forum, Colorado River Science Speaker Series. (Invited Talk)

Dibble, K.L., Rosenberg, D.E., and Schmidt, J.C., 2020, Colorado River fishes—Drivers, trends, and future uncertainties, CEE 6490—Integrated River Basins/Watershed Planning and Management, and Management of Large Rivers, WATS 5330/6330— virtual graduate class: Logan, Utah, April 3, 2020, Utah State University. (Invited Lecture)

Nelson, H., Ward, D.L., and Tennant, L., 2020, Can native Colorado River fish utilize New Zealand mudsnail as a food source?—poster presented at the Glen Canyon Dam Adaptive Management Group Annual Reporting meeting, January 13-15, 2020: Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

2019

Deemer, B.R., Hayes, N.M., Strock, K.E., Corman, J.R., Razavi, N.R., Dibble, K.L., and Yackulic, C.B., 2019, Catchment and management characteristics are key in determining reservoir response to climate change—presentation: San Juan, Puerto Rico, Feb 24-March 1, 2019, Association for the Sciences of Limnology and Oceanography. (Invited Talk)

Dibble, K.L., Yackulic, C.B., Schmidt, J.S., Kennedy, T.A., and Bestgen, K.R., 2019, Water storage decisions in response to drought in the Colorado River Basin will drive aquatic ecosystem dynamics—presentation: Reno, Nev., Sept 29-Oct 3, 2019, 149th American Fisheries Society Annual Meeting and Joint Conference with the Wildlife Society. (Invited Talk)

2018

Yackulic, C.B., Deemer, B.R., Yard, M.D., Dibble, K.L., Kennedy, T.A., and Hall, R.O., 2018, Drivers of the aquatic ecosystem in the Grand Canyon—The relative importance of flows, biotic interactions, temperature and nutrients—presentation: Logan, Utah, February 2018, Utah State University. (Invited Talk)

Yackulic, C.B., Deemer, B.R., Yard, M.D., Dibble, K.L., Kennedy, T.A., and Hall, R.O., 2018, Drivers of the aquatic ecosystem in the Grand Canyon—The underappreciated significance of phosphorous and the future of water temperatures—presentation: Flagstaff, September 2018, Northern Arizona University. (Invited Talk)

Journal Articles

2020

Dibble, K.L., C.B. Yackulic, J.C. Schmidt, T.A. Kennedy, and K.R. Bestgen, *2020, In press,* Water storage decisions will determine the distribution and persistence of imperiled river fishes: Ecological Applications.

Korman, J., Yard, M.D., Dzul, M.C., Yackulic, C.B., Dodrill, M.J., Deemer, B.R., and Kennedy, T.A., 2020, Changes in prey, turbidity, and competition reduce somatic growth and cause the collapse of a fish population: Ecological Monographs, online, https://doi.org/10.1002/ecm.1427.

Mihalevich, B.A., Neilson, B.T., Buahin C.A., Yackulic, C.B., Schmidt, J.C., *2020, In press,* Water temperature controls for regulated canyon-bound rivers: Water Resources Research.

Rüegg, J., Conn, C.C., Anderson, E.P., Battin, T.J., Bernhardt, E.S., Canadell, M.B., Bonjour, S.M., Hosen, J.D., Marzolf, N.S., and Yackulic, C.B., 2020, Thinking like a consumer—Linking aquatic basal metabolism and consumer dynamics: Limnology and Oceanography Letters, online, https://doi.org/10.1002/lol2.10172.

USGS Data Releases

Ryan, A., Ford, M., Muehlbauer, J., Kennedy, T., Deemer, B.R., 2020, Carbon, nitrogen, and phosphorus content of adult emergent Diptera before and after a fire-storm sequence in the Colorado River near Shinumo Creek, Grand Canyon, AZ: U.S. Geological Survey : U.S. Geological Survey data release, https://doi.org/10.5066/P9ODBTRV.

Project F Deliverables: Aquatic Invertebrate Ecology

Presentations

2020

Kennedy, T.A., 2020, Ecology of the Colorado River and Bug Flow monitoring results—WebEx presentation: Flagstaff, Ariz., May 2020, Virtual Guides Training Seminar, Grand Canyon River Guides.

Kennedy, T.A., 2020, Ecology of the Colorado River and Bug Flow monitoring results—WebEx presentation: Flagstaff, Ariz., September 1-15, 2020, Colorado River Days, hosted by Arizona Historical Society, http://www.coloradoriverdaysflagstaff.org/.

Kennedy, T.A., 2020, Little Bugs, big data, and Colorado River adaptive management—WebEx lecture: Logan, April 2020, Utah State University River Management class.

Kennedy, T.A., August 2020, The FLAHG hydrograph—WebEx presentation to the GCDAMP Adaptive Management Work Group: Flagstaff, Ariz., August 20, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/amwg/2020-08-20-amwg-meeting/20200820-TheFLAHGHydrograph-508-UCRO.pdf.

Kennedy, T.A., and Muehlbauer, J.D., 2020, Bug Flow monitoring results—WebEx presentation to the GCDAMP Technical Work Group, April 15, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/twg/2020-04-15-twg-meeting/20200415-BugFlowsMonitoringResults-Presentation-508-UCRO.pdf

Kennedy, T.A., and Muehlbauer, J.D., 2020, Year 2 of Bug Flows—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., January 13, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, https://www.usbr.gov/uc/progact/amp/twg/2020-01-13-twg-meeting/20200113-AnnualReportingMeeting-Year2BugFlows-Presentation-508-UCRO.pdf.

Lupoli, C.A., Kennedy, T.A., Muehlbauer, J.D., Sabo, J.L., and Yackulic, C.B., 2020, Exploring the effects of hydropeaking in the Flaming Gorge and Lees Ferry—virtual presentation: August 3-6, 2020, Ecological Society of American Annual Meeting, https://www.esa.org/saltlake/.

Metcalfe, A.N., Muehlbauer, J.D., Kennedy, T.A., Yackulic, C.B., Dibble, K.L., and Marks, J.C., 2020, Damming determines caddisfly distribution in a larger river basin—virtual presentation: August 3-6, 2020, Ecological Society of American Annual Meeting, https://www.esa.org/saltlake/.

Muehlbauer, J.D., 2020, Bug Flows—presentation: Flagstaff, Ariz., January 2020, Trout Unlimited/Arizona Flycasters Chapter Meeting.

Journal Articles

2020

Korman, J., Yard, M.D., Dzul, M.C., Yackulic, C.B., Dodrill, M.J., Deemer, B.R., and Kennedy, T.A., 2020, Changes in prey, turbidity, and competition reduce somatic growth and cause the collapse of a fish population: Ecological Monographs, online, https://doi.org/10.1002/ecm.1427.

Metcalfe, A.N., Muehlbauer, J.D., Kennedy, T.A., and Ford, M.A., 2020, Bug flows—Don't count your midges until they hatch: Boatman's Quarterly Review, v. 32, no. 4, winter 2019-2020, p. 8-11, https://www.researchgate.net/publication/339569673_Bug_flows_Don't_count_your_midges_until_they_hatch.

Metcalfe, A.N., Muehlbauer, J.D., Kennedy, T.A., Yackulic, C.B., Dibble, K.L., and Marks, J.C., 2020, Net-spinning caddisfly distribution in large regulated rivers: Freshwater Biology, p. 1-13, online, https://doi.org/10.1111/fwb.13617.

Miller, S.W., Schroer, M., Fleri, J.R., and Kennedy, T.A., 2020, Macroinvertebrate oviposition habitat selectivity and egg-mass desiccation tolerance—Implications for population dynamics in large regulated rivers: Freshwater Science, v. 39, no. 3, p. 584–599, https://doi.org/10.1086/710237.

Walters, D.M., Cross, W.F., Kennedy, T.A., Baxter, C.V., Hall, R.O., Jr., and Rosi, E.J., 2020, Food web controls on mercury fluxes and fate in the Colorado River, Grand Canyon: Science Advances, v. 6, no. 2, eaaz4880, p. 1-9, https://doi.org/10.1126/sciadv.aaz4880.

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

Presentations

2020

Bair, L.S., Donovan, P., Yackulic, C.B., Springborn, M.R., 2020, Managing for viable humpback chub populations via cost-effective invasive species control strategies—Adaptive management in the Grand Canyon: Durango, Colo., January 15, 2020, 40th Annual Researchers Meeting of the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program.

2019

Bair, L., Reimer, M., Donovan, P., Springborn, M., Bain, D., and Yackulic, C., 2019, Integrated assessment of ecosystem management and hydropower generation in endangered species recovery—presentation: Halifax, Nova Scotia, May 22-24, 2019, North American Association of Fisheries Economists Forum.

Dzul, M.C., Kendall, W., Winkelman, D., and Yackulic, C., 2019, Combining mark-recapture and PIT antenna detection data to assess ecological drivers of spawning in an endangered desert fish—presentation: Reno, NV, October 3, 2019, Joint Annual Conference of the American Fisheries Society and The Wildlife Society.

Dzul, M.C., Yackulic, C.B., Van Haverbeke, D.R., Kendall, W., and Winkelman, D., 2019, Environmental drivers of humpback chub population dynamics in the Colorado River and Little Colorado River—presentation: Flagstaff, Ariz. September 9-12, 2019, 15th Biennial Conference of Science and Management on the Colorado River Plateau and Southwest Region.

Yackulic, C.B., 2019, Using population models of interacting species to support decision makers—Taking the extra steps —presentation: Reno, Nev., Sept 29-Oct 3, 2019, Joint Annual Conference of the American Fisheries Society and The Wildlife Society.

Yackulic, C.B., Dodrill, M., Dzul, M., Sanderlin, J.S., and Reid, J.A. 2019, A need for speed in Bayesian population models—A practical guide to marginalizing discrete latent states—presentation: Reno, Nev., Sept 29-Oct 3, 2019, Joint Annual Conference of the American Fisheries Society and The Wildlife Society.

2018

Bair, L.S., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: Atlantic City, NJ, August 19-23, 2018, 148th Annual meeting of the American Fisheries Society.

Donovan, P., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: Vancouver, British Columbia, Canada, June 26-30, 2018, Western Economics 93rd Annual Conference.

Dzul, M.C., Yackulic, C.B., and Korman, J., 2018, Integrating data to improve understanding and management of rainbow trout and humpback chub in the lower Colorado River—presentation: Flagstaff, Ariz., February 2, 2018, 51st Joint Annual Meeting of the Arizona and New Mexico Chapters of the Wildlife Society and American Fisheries Society.

Springborn, M., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: Davis, Calif., March 2018, University of California, UC Davis Center for Population Biology Seminar Series.

Springborn, M., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: Vail, Colo., September 2018, University of Colorado, CU Environmental and Resource Economics Workshop.

Yackulic, C.B., Dodrill, M., and Dzul, M., 2018, Examining the trade-off between computational gains and reduced flexibility when marginalizing discrete latent states in Bayesian population models—presentation: Vancouver, Canada, July 29, 2018, Joint Statistical Meeting.

Journal Articles

2020

Dzul, M.C., Kendall, W.L., Yackulic, C.B., Winkelman, D.L., Conner, M., *In prep,* Incorporating antenna detections into abundance estimates of fish.

Dzul, M.C., Kendall, W.L, Yackulic, C.B., Winkelman, D.L, Van Haverbeke, D.R., and Yard, M., *In review,* Partial migration and spawning movements of humpback chub in the Little Colorado River are better understood using data from autonomous PIT tag antennas: Canadian Journal of Fisheries and Aquatic Sciences.

Stone, D.M., Pillow, M.J., Young, K.L., Van Haverbeke, D.R., and Walters, J.D., 2020, Effects of disparate water temperatures and food bases on humpback chub growth rates within the Little Colorado River, Arizona: North American Journal of Fisheries Management, v. 40, no. 2, p. 475-497, https://doi.org/10.1002/nafm.10425.

Ward, D.L., and Ward, M.B., 2020, What's in the hump of the humpback chub?: Western North American Naturalist, v. 80, no. 1, article 12, p. 98-104, https://doi.org/10.3398/064.080.0112

Yackulic, C.B., Dodrill, M.J., Dzul, M.C., Sanderlin, J., and Reid, J., 2020, A need for speed in Bayesian population models—A practical guide to marginalizing and recovering discrete latent states: Ecological Applications, v. 30, no. 5, e02112, p. 1-19, https://doi.org/10.1002/eap.2112.

Yackulic, C.B., Van Haverbeke, D.R., Dzul, M.C., Bair, L. and Young, K., *In review*, Assessing the population impacts and cost-effectiveness of a conservation translocation: Journal of Applied Ecology.

2019

Behn, K.E., and Baxter, C.E., 2019, The trophic ecology of a desert river fish assemblage—Influence of season and hydrologic variability: Ecosphere, v. 10, no. 1, e02583, p. 1-24, https://doi.org/10.1002/ecs2.2583.

Donovan,P., Bair, L.S., Yackulic, C.B., and Springborn, M.R., 2019, Safety in numbers—Applying chance-constrained dynamic programming to population viability analysis and adaptive management: Land Economics, v. 95, no. 3, p. 435-453, https://doi.org/10.3368/le.95.3.435.

Donovan, P., and Springborn, M.R., 2019, Maintaining the long-term viability of the humpback chub in the Grand Canyon: ARE Update, University of California, Giannini Foundation of Agricultural Economics, v. 22, no. 5, p. 5-8, https://giannini.ucop.edu/publications/are-update/issues/2019/22/5/maintaining-the-long-term-viability-of-the-humpbac/.

Tennant, L.A., Vaage, B.M., and Ward, D.L., 2019, An evaluation of sedatives for use in transport of juvenile endangered fishes in plastic bags: Journal of Fish and Wildlife Management, v. 10, no. 2, p. 532-543, https://doi.org/10.3996/032019-JFWM-016.

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

2018

Brizendine, M.E., Ward, D.L., and Bonar, S.A., 2018, Effectiveness of ultrasonic imaging for evaluating presence and maturity of eggs in fishes in remote field locations: North American Journal of Fisheries Management, v. 38, no. 5, p. 1017-1026, https://doi.org/10.1002/nafm.10200.

Stone, D.M., Young, K.L., Mattes, W.P., and Cantrell, M.A., 2018, Abiotic controls of invasive nonnative fishes in the Little Colorado River, Arizona: The American Midland Naturalist, v. 180, no. 1, p. 119-142, https://doi.org/10.1674/0003-0031-180.1.119.

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

2017

Van Haverbeke, D.R., Stone, D.M., Dodrill, M.J., Young, K.L., and Pillow, M.J., 2017, Population expansion of humpback chub in western Grand Canyon and hypothesized mechanisms: The Southwestern Naturalist, v. 62, no. 4, p. 285-292, https://doi.org/10.1894/0038-4909-62.4.285.

USGS Reports

Yackulic, C.B., and Hull, J.B., 2019, Effects of water temperature, turbidity, and rainbow trout on humpback chub population dynamics: U.S. Geological Survey Fact Sheet 2019-3049, 4 p., https://doi.org/10.3133/fs20193049.

Cooperator Reports (USFWS)

2020

Pillow, M.J., and Williams, O.F., 2020, Fall 2019 monitoring and translocation of humpback chub (*Gila cypha*) in the lower 13.57 km of the Little Colorado River, Arizona—trip report for September 17-27 and October 15-25, 2019: Flagstaff, Ariz., U.S. Fish and Wildlife Service, prepared for U.S. Geological Survey, Grand Canyon Monitoring and Research Center, USFWS document no. USFWS-AZFWCO-FL-20-01, 10 p.

Van Haverbeke, D.R., Pillow, M.J., and Young, K.L., 2020, Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2019: Flagstaff, Arizona Fish and Wildlife Conservation Office, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Van Haverbeke, D.R., Young, K.L., Pillow, M.J., and Williams, O., 2020, Monitoring humpback chub aggregations in the Colorado River, Grand Canyon during fall 2019: Flagstaff, Ariz., U.S. Fish and Wildlife Service, 39 p.

Van Haverbeke, D.R., Young, K.L., Stone, D.M., Pillow, M.J., and Williams, O.F., 2020, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2019: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, USFWS no. USFWS-AZFWCO-FL-20-02, 47 p.

2019

Pillow, M.J., 2019, Spring 2019 monitoring of humpback chub (*Gila cypha*) and other fishes in the lower 13.57 km of the Little Colorado River, Arizona—trip report for April 16-26 and May 14-24, 2019: Flagstaff, Ariz., submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, USFWS Document No. USFWS-AZFWCO-FL-19-04, 11 p.

Stone, D.M., 2019, Spring 2019 monitoring of humpback chub (*Gila cypha*) and other fishes above Lower Atomizer Falls in the Little Colorado River, Arizona—trip report for April 16-26 and May 14-24, 2019: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Interagency acquisition no. G17PG00059, document no. USFWS-AZFWCO-FL-19-04, 11 p.

Van Haverbeke, D.R., Young, K.L., Stone, D.M., and Pillow, M.J., 2019, Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, document no. USFWS-AZFWCO-FL-19-02, 46 p.

2018

Pillow, M.J., and Stone, D.M., 2018, Fall 2018 monitoring and translocation of humpback chub (*Gila cypha*) in the lower 13.57 km of the Little Colorado River, Arizona—trip report for September 18-28 and October 24-30, 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service, prepared for U.S. Geological Survey, Grand Canyon Monitoring and Research Center, USFWS document no. USFWS-AZFWCO-FL-19-01, 11 p.

Pillow, M.J., Van Haverbeke, D.R., and Young, K.L., 2018, Monitoring humpback chub in the Colorado River, Grand Canyon, August 19-September 4, 2017: Flagstaff, Arizona Fish and Wildlife Conservation Office, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, USFWS document no. USFWS-AZFWCO-18-05, 26 p.

Stone, D.M., 2018, Fall 2018 monitoring of humpback chub (*Gila cypha*) and other fishes in the lower 13.57 km of the Little Colorado River: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Stone, D.M., 2018, Spring 2018 monitoring of humpback chub (*Gila cypha*) and other fishes above Lower Atomizer Falls in the Little Colorado River, Arizona—trip report for May 15-24, 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, document no. USFWS-AZFWCO-FL-19-04, 14 p., http://gcdamp.com/images_gcdamp_com/e/ec/HBC_Monitoring_above_Lower_Atomizer_Falls_2018_Trip_Report.pdf.

<u>USGS Data Releases</u>

2020

Yackulic, C.B., Dzul, M.C, Reid, J.A., Sanderlin, J.S., Block, W.M., Ganey, J.L., Dodrill, M.J., and Yard, M.D., 2020, Marginalizing bayesian population models—data for examples in the Grand Canyon region, southeastern Arizona, and western Oregon, USA - 1990-2015: U.S. Geological Survey data release, https://doi.org/10.5066/P9JN5C0L.

2018

Yackulic, C. B. 2018. Humpback chub (*Gila cypha*) and rainbow trout (*Oncorhynchus mykiss*) joint mark-recapture data and model: U.S. Geological Survey data release, Colorado River, Arizona. https://doi.org/10.5066/f7zc81t9.

Project H Deliverables: Salmonid Research and Monitoring

Presentations

2020

Korman, J. and Yard, M., 2020, What determines the abundance of rainbow trout near the Little Colorado River confluence?—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., January 12-13, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Yard, M.D., and Korman, J, 2020, Glen Canyon trout populations—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., January 12-13, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Yard, M.D., and Korman, J, 2020, The trout fishery, recruitment, growth and population dynamics—A review of the key takeaways from the Annual Reporting Meeting and an opportunity for additional discussion—virtual presentation for the GCDAMP Technical Working Group: April 15, 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center. (Project Element H.1, Recruitment, growth and population dynamics)

2019

Kennedy, T.A., Muehlbauer, J.D., and Rogowski, D.L., 2019, Colorado River ecosystem responses to the 2018 Bug Flow experiment from Glen Canyon Dam: Flagstaff, Ariz., Sept 9-12, 2019, 15th Biennial Conference of Science Management on the Colorado Plateau and Southwest Region.

Korman, J., and Yard, M., 2019, Trout management flows—A review of data, research results, and information needs—presentation to the GCDAMP Technical Working Group: Phoenix, Ariz., June 11-12, 2019, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

2018

Dibble, K.L., and Yackulic, C.B., 2018, Examining the influence of experimental floods on the growth and physiological condition of juvenile rainbow trout—presentation: Atlantic City, NJ, August 19-23, 2018, 148th Annual Meeting of the American Fisheries Society.

Journal Articles

2020

Korman, J., Yard, M.D., Dzul, M.C., Yackulic, C.B., Dodrill, M.J., Deemer, B.R., and Kennedy, T.A., 2020, Changes in prey, turbidity, and competition reduce somatic growth and cause the collapse of a fish population: Ecological Monographs, online, https://doi.org/10.1002/ecm.1427.

Korman, J., Yard, M.D., Dzul, M.C., Yackulic, C.B., Dodrill, M.D., Deemer, B.R., and Kennedy, T.A., *In press*, Controls on somatic growth and population dynamics of rainbow trout: The Bulletin of the Ecological Society of America.

Yackulic, C.B., Dodrill, M.J., Dzul, M.C., Sanderlin, J., and Reid, J., 2020, A need for speed in Bayesian population models—A practical guide to marginalizing and recovering discrete latent states: Ecological Applications, v. 30, no. 5, e02112, p. 1-19, https://doi.org/10.1002/eap.2112.

Cooperator Reports

2018

Boyer, J.K., and Rogowski, D.L., 2019, Status of the Lees Ferry rainbow trout fishery—2018 annual report: Phoenix, Arizona Game and Fish Department, 40 p., https://www.researchgate.net/publication/333634720_STATUS_OF_THE_LEES_FERRY_RAINBOW_TROUT_FISHERY_2018_ANNUAL_REPORT.

USGS Reports

2018

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

USGS Data Releases

2018

Yackulic, C.B., Korman, J., and Coggins, L., 2018, Population dynamics of humpback chub, rainbow trout and brown trout in the Colorado River in its Grand Canyon Reach—Modelling code and input data: U.S. Geological Survey data release, https://doi.org/10.5066/F7FN15HC.

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

Presentations

2020

Boyer, J.K., 2020, Falling water, rising temperatures, growing fish?—presentation: Laughlin, NV, January 2020, Colorado River Area Biologist annual meeting.

Boyer, J.K., and others, 2020, Arizona Game and Fish Grand Canyon Monitoring—presentation at the GCDAMP Annual Reporting Meeting: Phoenix, Ariz., January 2020, U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

Rogowski, D.L., and Boyer, J.K., 2020, Is Pearce Ferry Rapid a barrier to fishes in the Colorado River?—presentation: Laughlin, NV, January 2020, Colorado River Area Biologist annual meeting.

Rogowski, D.L., and Boyer, J.K., 2020, Is Pearce Ferry Rapid a barrier to fishes in the Colorado River?—presentation: Prescott, Ariz., February 2020, Joint Annual Meeting of AZ and NM Wildlife and American Fisheries Annual Meeting.

Rogowski, D.L., 2020, Native fish recovery in a highly regulated river—presentation: Flagstaff, University of Arizona, February 7, 2020, NAU Biology Seminar Series.

Ward, D.L., 2020, Colorado river native fishes and introduced sportfish—Immiscible or emulsion?—presentation: Laughlin, NV, January 2020, Colorado River Area Biologist annual meeting.

Ward, D.L., 2020, Interactions between native and nonnative fishes in Arizona—presentation: Flagstaff, Northern Arizona University, Forestry Department, Ecological Restoration 382.

Journal Articles

2020

Tennant, L.A., Ward, D.L., and Gibb, A.C., *In press*, Comparison of electrofishing and PIT antennas for detection of hatchery-reared roundtail chub (*Gila robusta*) stocked into a desert stream: Arizona/Nevada Academy of Science.

Rogowski, D.R., and Boyer, J.K., *In review,* Can sexual condition and behavior bias results from passive fish traps?: submitted to North American Journal of Fisheries Management.

Ward, D.L., and Ward, M.B., 2020, What's in the hump of the humpback chub?: Western North American Naturalist, v. 80, no. 1, article 12, p. 98-104, https://doi.org/10.3398/064.080.0112.

Cooperator Reports

2020

Boyer, J.K., and Rogowski, D.L., 2020, Colorado River fish monitoring in Grand Canyon, Arizona—2019 annual report: Phoenix, Ariz., Arizona Game and Fish Department, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 32 p., https://www.researchgate.net/publication/333634628_Colorado_River_Fish_Monitoring_in_the_Grand_Canyon_Arizona-2018_Annual_Report.

Project J Deliverables: Socioeconomic Research in the Colorado River Ecosystem

Presentations

2020

Bair, L., 2020, U.S. Tribal and USGS Cooperation—An overview of using USGS Science by Tribal communities for floods and cascading hazards—virtual workshop: Indigenous Perspectives on Flood Damages and Losses, July 2020, Costing Floods and Other Extreme Events, Commission for Environmental Cooperation.

Bair, L., Reimer, M., Donovan, P., Springborn, M., Bain, D., and Yackulic, C., 2020, Managing for viable humpback chub populations via cost-effective invasive species control strategies—Adaptive management in the Grand Canyon: Durango, Colo., January 15, 2020, 40th Annual Researchers Meeting of the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program.

2019

Bair, L., Reimer, M., Donovan, P., Springborn, M., Bain, D. and Yackulic, C., 2019, Integrated assessment of ecosystem management and hydropower generation in endangered species recovery: Halifax, Nova Scotia, May 22-24, 2019, North American Association of Fisheries Economists Forum.

Huber, C., Bair, L.S., Arviso-Ciocco, M., Neher, C.J., and Duffield, J.W., 2019, Tribal preferences for Colorado River water management and the Glen Canyon Dam—presentation: Flagstaff, Ariz., September 9-12, 2019, 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region.

2018

Bair, L., 2018, Peoples' values and objectives for river use—An example from the Colorado River in Grand Canyon—presentation: Palmas, Brazil, May 15-16, 2018, Workshop on Rivers, Lands and Cultures—Learning from the Tocantins Social-ecological System, Federal University of Tocantins.

Bair, L., Reimer, M., and Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: Atlantic City, NJ, August 23, 2018, American Fisheries Society, 148th Annual Meeting, https://afs.confex.com/afs/2018/meetingapp.cgi/Paper/33683.

Bair, L., Reimer, M., and Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: Washington, D.C., September 26, 2018, Department of Interior Economics Workshop.

Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: Vail, Colo., September 13-14, 2018, CU Environmental and Resource Economics Workshop.

Springborn, M., Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: Davis, Calif., March 2018, UC Davis Center for Population Biology Seminar Series.

Springborn, M., Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: Vancouver, British Columbia, Canada, June 26-30, 2018, Western Economics 93rd Annual Conference.

Journal Articles

2020

Yackulic, C.B., Van Haverbeke, D.R., Dzul, M.C., Bair, L., and Young, K., *In review*, Assessing the population impacts and cost-effectiveness of a conservation translocation: Journal of Applied Ecology.

2019

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

2018

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

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

2017

Neher, C., Duffield, J., Bair, L.S., Patterson, D., and Neher, K., 2017, Testing the limits of temporal stability—Willingness to pay values among Grand Canyon whitewater boaters across decades: Water Resource Research, v. 53, no. 12, p. 10108-10120, http://dx.doi.org/10.1002/2017WR020729.

Cooperator Reports

2019

Donovan, P., and Springborn, M.R., 2019, Maintaining the long-term viability of humpback chub in the Grand Canyon: ARE Update, University of California Giannini Foundation of Agricultural Economics, v. 22, no. 5, p. 5-8, https://giannini.ucop.edu/publications/are-update/issues/2019/22/5/maintaining-the-long-term-viability-of-the-humpbac/.

Project K Deliverables: Geospatial Science and Technology

Presentations

2020

Gushue, T.M., Hensleigh, J., 2020, Improving water quality monitoring through new technologies—Lake Powell and Glen Canyon, Arizona—virtual presentation on the new EarthMAP initiative for USGS: September 15-17, 2020, USGS Rocky Mountain Region Science Exchange Workshop, Setting the Stage for EarthMAP in the Colorado River Basin and the Rocky Mountain Region.

2018

Gushue, T.M., 2018, Grand Canyon Internet of Things (IoT) pilot project at Lees Ferry, Arizona—presentation: Denver, Colo., June 2018, USGS Sensor Summit Workshop.

USGS Data Releases

2019

Gushue, T.M., 2019, Colorado River Mile System, Grand Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9IRL3GV.

Web Applications

2018

Gushue, T.M., 2018, Predicted shorelines for high flows web application: online October 2018, https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=721001c63d91458883340f05c68c55f4.

Gushue, T.M., 2018, Sandbar area and volume web application: online October 2018, currently under construction due to changes in AWS architecture.

Websites

2020

GCMRC geospatial REST services page, online July 2020, https://grandcanyon.usgs.gov/gisapps/restservices/index_wret.html.

Grand Canyon geospatial portal (upgraded), online August 2020, https://grandcanyon.usgs.gov/portal/home/index.html.

Grand Canyon geospatial server (upgraded), online August 2020, https://grandcanyon.usgs.gov/server/rest/services.

2019

GCMRC home page, online May 2019, https://www.usgs.gov/centers/sbsc/gcmrc.

GCMRC data and tools landing page, online May 2019, https://www.usgs.gov/centers/sbsc/science/gcmrc-data-and-tools?qt-science_center_objects=0#qt-science_center_objects.

GCDAMP landing page for USGS-GCMRC, online April 2019, https://www.usgs.gov/centers/sbsc/science/glen-canyon-dam-adaptive-management-program-gcdamp.

GCMRC projects landing page, online May 2019, https://www.usgs.gov/centers/sbsc/science/grand-canyon-monitoring-and-research-projects?qt-science_center_objects=0#qt-science_center_objects.

GCMRC scientist and staff directory webpage, online May 2019, https://www.usgs.gov/centers/sbsc/science/gcmrc-scientist-staff-directory?qt-science_center_objects=0#qt-science_center_objects.

Project N Deliverables: Hydropower Monitoring and Research

Presentations

2020

Bair, L., 2020, Identifying the total economic value of hydropower and implications for adaptive management of rivers—virtual webinar presentation: April 3, 2020, Adaptive Management of Hydropower Plants—Principles and Examples, International Research Network on Amazonian Dams, Amazon Dams Network.

Bair, L., Reimer, M., Donovan, P., Springborn, M., Bain, D., and Yackulic, C., 2020, Managing for viable humpback chub populations via cost-effective invasive species control strategies—Adaptive management in the Grand Canyon—presentation: Durango, Colo., January 15, 2020, 40th Annual Researchers Meeting of the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program.

2019

Bair, L. and Bain, D., 2019, Identifying the value of hydropower in the electricity sector and implications for environmental management of rivers—presentation: Flagstaff, AZ, September 9-12, 2019, 15th Biennial Conference of Science and Management on the Colorado Plateau and Southwest Region.

Bair, L., Reimer, M., Donovan, P., Springborn, M., Bain, D., and Yackulic, C., 2019, Integrated assessment of ecosystem management and hydropower generation in endangered species recovery—presentation: Halifax, Nova Scotia, May 22-24, 2019, North American Association of Fisheries Economists Forum.

2018

Bair, L., Reimer, M., Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: Atlantic City, NJ, August 19-23, 2018, American Fisheries Society, 148th Annual Meeting.

Bair, L., Reimer, M., Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: Washington, D.C., September 2018, Department of the Interior Economics Workshop.

Journal Articles

2020

Waldo, S., Deemer, B.R., Bair, L., and J. Beaulieu, *2020, In Revision,* 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.

Appendix 1 Deliverables: Lake Powell Water Quality Monitoring

Presentations

2019

Marinelli, M.B., Strock, K.E.D., and Deemer, B.R., 2019, Shifting phytoplankton and zooplankton phenology in recent decades in Lake Powell reservoir, southwestern USA—poster: Louisville, KY, August 13, 2019, Ecological Society of America Meeting.

2018

Deemer, B.R., Stets, E., and Yackulic, C.B., 2018, Lake Powell significantly reduces the concentration, seasonal variation, and downstream transport of major cations and anions in the Colorado River—presentation: Victoria, B.C., June 12, 2018, Association for the Sciences of Limnology and Oceanography Meeting.

Deemer, B.R., and Yackulic, C.B., 2018, Lake Powell—A critical biogeochemical regulator of downstream ecosystems—poster: Rottnest Island, Australia, December 5, 2018, Global Lakes Ecological Observatory Network Meeting.

Journal Articles

2020

Deemer, B.R., Stets, E.G., and Yackulic, C.B., 2020, Calcite precipitation in Lake Powell reduces alkalinity and total salt loading to the Lower Colorado River Basin: Limnology and Oceanography, v. 65, p. 1439-1455, https://doi.org/10.1002/lno.11399.

Waldo, S., Deemer, B.R., Bair, L., and J. Beaulieu, *2020, In Revision,* 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.

USGS Data Releases

2020

Deemer, B.R., Waldo, S., and Gushue, T., *In prep*, Greenhouse gas emissions from Lake Powell and Lake Mead—Model inputs, limnological data, and bathymetric analysis: U.S. Geological Survey data release, https://doi.org/10.5066/P9PRW8JX.

2019

Deemer, B.R., 2019, Calcium, magnesium and total dissolved solids data as well as modeled salinity and mass balance estimates for Lake Powell, 1952-2017: U.S. Geological Survey data release, https://doi.org/10.5066/P9A9P44R.

Web Applications

2020

Hensleigh, J., Voichick, N., and Deemer, B., *In beta testing*, Lake Powell vertical water quality profiles—1965-2020: Tableau.

Appendix 3: Budgets, All Projects

Project A

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$561,750	$10,400	$72,600	$0	$426,600	$88,937	**$1,160,287**
Actual Spent	$623,234	$2,341	$46,747	$0	$388,543	$92,740	**$1,153,605**
(Over)/Under Budget	**($61,484)**	**$8,059**	**$25,853**	**$0**	**$38,057**	**($3,803)**	**$6,682**
FY19 Carryover	**$0**					**FY20 Carryover**	**$6,682**

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

- Higher costs for salary were due to the need for increased overtime as a result of back log of processing of samples from previous years.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.
- Lower costs in funding to other USGS Centers was due to additional funding being allocated in FY2019 for additional discharge work and database programming which was necessary to fully inform suspended sediment concentrations and budgets.

Project B

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$477,421	$5,900	$27,000	$374,126	$0	$81,617	**$966,064**
Actual Spent	$325,273	$5,101	$21,881	$816,763	$0	$73,093	**$1,242,111**
(Over)/Under Budget	**$152,148**	**$799**	**$5,119**	**($442,638)**	**$0**	**$8,524**	**($276,048)**
FY19 Carryover	**$392,821**					**FY20 Carryover**	**$116,773**

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

- Lower costs in salary was due to a vacancy. This work was accomplished through cooperative agreements.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.
- Higher costs in cooperative agreements was due to additional funding to conduct work associated with a vacancy at GCMRC and the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project C

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$240,738	$850	$2,500	$180,273	$0	$39,078	**$463,439**
Actual Spent	$212,540	$873	$3,111	$361,425	$0	$40,710	**$618,659**
(Over)/Under Budget	**$28,198**	**($23)**	**($611)**	**($181,152)**	**$0**	**($1,632)**	**($155,220)**
FY19 Carryover	**$267,364**					**FY20 Carryover**	**$112,144**

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

- Lower costs in salary was due to a vacancy and one staff member serving on a detail. Work related to the vacancy was accomplished through cooperative agreements.
- Higher costs in cooperative agreements was due to additional funding to conduct work associated with a vacancy at GCMRC and the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project D

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$207,609	$4,750	$7,100	$0	$0	$30,272	**$249,731**
Actual Spent	$218,498	$601	$3,041	$0	$0	$30,642	**$252,782**
(Over)/Under Budget	**($10,889)**	**$4,149**	**$4,059**	**$0**	**$0**	**($370)**	**($3,051)**
FY19 Carryover	**$18,141**					**FY20 Carryover**	**$15,090**

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

- Higher costs for salary was due to unanticipated effort maintaining instrumentation in support of this and other projects that require remote access to sensors near Lees Ferry.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to lack of need to purchase new field equipment.

Project E

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$187,142	$6,000	$36,497	$10,000	$0	$31,976	**$271,615**
Actual Spent	$176,846	$3,803	$20,146	$12,000	$0	$28,058	**$240,853**
(Over)/Under Budget	**$10,296**	**$2,197**	**$16,351**	**($2,000)**	**$0**	**$3,918**	**$30,762**
FY19 Carryover	**$91,973**					FY20 Carryover	**$122,735**

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

- Lower costs in salaries was due to a vacancy. Work was accomplished through a cooperative agreement.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Lower costs in operating expenses was due to the lack of monsoon storms and associated tributary flooding which led to the cancellation of planned field sampling and in turn eliminated the need to purchase field supplies or pay for sample analyses.

Project F

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$547,192	$20,316	$30,244	$0	$0	$82,454	**$680,206**
Actual Spent	$683,113	$9,454	$44,940	$0	$0	$101,732	**$839,239**
(Over)/Under Budget	**($135,921)**	**$10,862**	**($14,696)**	**$0**	**$0**	**($19,278)**	**($159,033)**
FY19 Carryover	**($7,534)**					FY20 Carryover	**($166,567)**

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

- Higher costs for salary were due to the need for additional staff and increased overtime as a result of processing of aquatic food base samples from the Bug Flow experiment in 2019 and 2020 including additional samples collected for tasks added to the original study design at the request of cooperators and stakeholders.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs of operating expenses were due to the need to purchase field equipment that had failed.
- The lack of anticipated Experimental Funds in FY2020 constitutes the overall budget shortfall for Project F.

Project G

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$424,185	$2,000	$62,000	$520,666	$0	$82,960	**$1,091,811**
Actual Spent	$321,092	$3,947	$34,629	$955,273	$0	$78,271	**$1,393,212**
(Over)/Under Budget	**$103,093**	**($1,947)**	**$27,371**	**($434,607)**	**$0**	**$4,689**	**($301,401)**
FY19 Carryover	**$551,216**					**FY20 Carryover**	**$249,815**

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

- Lower costs in salary was due to needed field staff being provided by contractors instead of USGS employees. These costs are accounted for under the Logistics budget.
- Lower costs in operating expenses was due to the lack of a need to purchase planned for field equipment and supplies for trips cancelled due to COVID-19 closure of the Colorado River in Grand Canyon.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project H

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$272,040	$7,236	$25,160	$148,000	$0	$46,434	**$498,870**
Actual Spent	$170,405	$2,068	$67,592	$246,000	$0	$40,495	**$526,560**
(Over)/Under Budget	**$101,635**	**$5,168**	**($42,432)**	**($98,000)**	**$0**	**$5,939**	**($27,690)**
FY19 Carryover	**$134,637**					**FY20 Carryover**	**$106,947**

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

- Lower costs in salary was due to needed field staff being provided by contractors instead of USGS employees and part of the salary of a vacancy. These contractor costs are accounted for under the Logistics budget.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs of operating expenses was due to the need to shift a cooperative agreement to a service contract which falls in this budgeting category.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project I

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$184,998	$2,500	$22,000	$238,550	$0	$36,055	**$484,103**
Actual Spent	$195,471	$2,976	$12,953	$173,508	$0	$34,366	**$419,274**
(Over)/Under Budget	**($10,473)**	**($476)**	**$9,047**	**$65,042**	**$0**	**$1,689**	**$64,829**
FY19 Carryover	**$213,932**					**FY20 Carryover**	**$278,761**

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

- Higher costs for salary were due to the inability to use as many volunteers as planned because of COVID-19 restrictions and had to rely on existing staff for field labor.
- Lower costs in operating expenses was due to the lack of a need to purchase equipment planned for field equipment and supplies for trips cancelled due to COVID-19 closures of the Colorado River in Grand Canyon and Navajo Nation lands.
- Lower costs in cooperative agreements was due to the requirement for GCMRC to receive approval from the USGS Director to fund the agreement which did not occur before the end of FY2020. GCMRC plans to transfer funds to the cooperator in FY2021.

Project J

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$141,904	$3,250	$1,125	$71,500	$0	$22,323	**$240,102**
Actual Spent	$138,036	$2,358	$2,516	$128,548	$0	$23,569	**$295,027**
(Over)/Under Budget	**$3,868**	**$892**	**($1,391)**	**($57,048)**	**$0**	**($1,246)**	**($54,925)**
FY19 Carryover	**$93,462**					**FY20 Carryover**	**$38,537**

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

- Lower costs in salary was due to part of the Principal Investigator's salary being covered by a non-GCDAMP project.
- Higher costs for operating expenses were due to the need to purchase additional supplies for Tribal meetings that had been delayed from a previous year.
- Higher costs in cooperative agreements was due to the requirement for GCMRC to move FY2019 funds from an expiring 5-year agreement between USGS and Reclamation to a new one. As previously planned, funds were transferred to the cooperator in FY2020.

Project K

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$260,304	$4,000	$11,850	$0	$0	$38,093	**$314,247**
Actual Spent	$206,947	$0	$14,301	$0	$0	$30,519	**$251,767**
(Over)/Under Budget	**$53,357**	**$4,000**	**($2,451)**	**$0**	**$0**	**$7,574**	**$62,480**
FY19 Carryover	**$53,497**					**FY20 Carryover**	**$115,977**

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

- Lower costs in salary was due to a vacancy. Position will be refilled in FY2021.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs for operating expenses were due to the need to purchase new equipment that had failed.

Project L

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$0	$0	$0	$75,000	$0	$0	**$75,000**
Actual Spent	$0	$0	$0	$0	$0	$0	**$0**
(Over)/Under Budget	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$0**	**$75,000**
FY19 Carryover	**$225,000**					**FY20 Carryover**	**$300,000**

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

- Lower costs in cooperative agreements was due to planned carryover of funds budgeted in FYs 2018, 2019, and 2020, in the amount of $75,000 each year, in support of the remote sensing overflight of Grand Canyon planned for FY2021. Funds were deobligated to Reclamation and will be held there until needed to fund the overflight.

Project M

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$683,711	$42,000	$236,000	$0	$0	$132,658	**$1,094,369**
Actual Spent	$651,953	$17,145	$288,568	$0	$0	$132,100	**$1,089,766**
(Over)/Under Budget	**$31,758**	**$24,855**	**($52,568)**	**$0**	**$0**	**$558**	**$4,603**
FY19 Carryover	**$54,940**					**FY20 Carryover**	**$59,543**

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

- Lower costs in salary due to a staff member serving on a detail and USGS providing some funding for GCMRC leadership salaries in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2021 funding.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs in operating expenses due to the requirement of USGS to pay contract administrative fees associated with a labor dispute with the Department of Labor regarding salary rates in GCMRC's boat operations contract.

Project N

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$9,863	$750	$375	$0	$0	$1,516	**$12,504**
Actual Spent	$9,860	$0	$0	$0	$0	$1,360	**$11,220**
(Over)/Under Budget	**$3**	**$750**	**$375**	**$0**	**$0**	**$156**	**$1,284**
FY19 Carryover	**$686**					**FY20 Carryover**	**$1,970**

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

- Lower costs for travel and training was due to travel restrictions associated with COVID-19.

Appendix 1 – Lake Powell (Not GCDAMP funded)

Lake Powell (NOT GCDAMP funded)							
	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 21.733%	Total
Budgeted Amount	$147,187	$9,109	$10,951	$0	$0	$36,348	**$203,595**
Actual Spent	$128,607	$2,474	$9,526	$0	$0	$30,558	**$171,165**
(Over)/Under Budget	**$18,580**	**$6,635**	**$1,425**	**$0**	**$0**	**$5,790**	**$32,430**
FY19 Carryover	**$145,652**					FY20 Carryover	**$178,082**

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

- This project is funded entirely by Reclamation with **non-GCDAMP funding**.
- High carryover amounts from one fiscal year to another are an artifact of this project being budgeted on calendar years rather than fiscal years.

Logistics

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 13.794%	Total
Budgeted Amount	$267,078	$6,000	$905,786	$11,000	$0	$162,943	**$1,352,807**
Actual Spent	$272,192	$2,474	$1,232,757	$11,000	$0	$208,264	**$1,726,687**
(Over)/Under Budget	**($5,114)**	**$3,526**	**($326,971)**	**$0**	**$0**	**($45,321)**	**($373,880)**
FY19 Carryover	**$381,337**					FY20 Carryover	**$7,457**

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

- Higher costs in salary due to retaining a retiree part time to help train new Logistics Coordinator.
- Lower costs for travel and training was due to travel restrictions associated with COVID-19.
- Higher costs for operating expenses were due to needed field staff for several project being provided by contractors instead of USGS employees which are funded through GCMRC's boat operations contract.

Budget Summary – Adaptive Management Program Total

Budget Summary Adaptive Management Program Total (without Lake Powell agreement)							
Total	**Salaries**	**Travel & Training**	**Operating Expenses**	**Cooperative Agreements**	**To other USGS Centers**	**Burden 13.794%**	**Total**
Budgeted Amount	$4,465,934	$115,952	$1,440,237	$1,629,115	$426,600	$879,565	**$8,957,403**
Actual Spent	$4,205,460	$53,141	$1,793,182	$2,704,518	$388,543	$915,918	**$10,060,762**
(Over)/Under Budget	$260,474	$62,811	($352,945)	($1,075,403)	$38,057	**($36,353)**	**($1,103,359)**
FY19 Carryover	**$2,471,472**					**FY20 Carryover**	**$1,365,863**
COMMENTS *(Discuss anomalies in the budget; expected changes; anticipated carryover; etc.)*							

- High FY2019 carryover and higher than projected spending in FY2020 is primarily a result of funding not being sent to several cooperators including USFWS, AGFD, and NAU in FY2019 but instead in FY2020. The 5-year Interagency Agreement between Reclamation and USGS that funds GCMRC expired at the end of FY2019 and a new agreement was established. Cooperator funding from the old agreement was only valid through the end of FY2019. Remaining funds were deobligated and then reobligated into the new agreement with the intent of funding cooperators in FY2020.