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

Fiscal Year 2019
Annual Project Report

to the

Glen Canyon Dam
Adaptive Management
Program

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Introduction

Following is the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center's (GCMRC) Fiscal Year (FY) 2019 Annual Accomplishment Report. This report is prepared primarily for the Bureau of Reclamation to account for work conducted and products delivered in FY 2019 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.

It includes a summary of accomplishments, modifications, results, and recommendations related to projects included in GCMRC's FY 2018-2020 Triennial Work Plan for FY 2019[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 (Table 1). The report also contains a summary of deobligation/reobligation funding amounts for specific projects that resulted from the transition to the new 5-year funding agreement with the Bureau of Reclamation in FY 2020 (Tables A & B).

[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.

LTEMP Resource Goals: Table 1

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.

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

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

SUMMARY

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 Colorado River ecosystem (CRe). These data are collected to address the Glen Canyon Dam Adaptive Management Program (GCDAMP) Goal 7 and the Long-Term Experimental and Management Plan (LTEMP) Sediment Goal. 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 are used by other projects funded by the GCDAMP to address the LTEMP goals for archaeological and cultural resources, natural processes, humpback chub, other native fish, recreational experience, rainbow trout fishery, nonnative invasive species, and riparian vegetation. The high-resolution suspended-sediment data collected under this project are used to construct the mass-balance sediment budgets used by managers to trigger, design, and evaluate High-Flow Experiments (HFEs) under the High-Flow Protocol included in the 2016 LTEMP Record of Decision. Details of this ongoing project (including descriptions of the data-collection locations) are provided in the GCMRC fiscal year (FY) 2018–20 Triennial Work Plan (TWP).

Science Question Addressed

The Streamflow, Water Quality, and Sediment Transport and Budgeting in the CRe Project addresses the following fundamental science question on an ongoing basis:

> *How do operations at Glen Canyon Dam affect flows, water quality, sediment transport, and sediment resources in the CRe?*

During FY 2019, this question was addressed through these methods:

1) All FY 2019 monitoring data required by this project, including those required to evaluate the November 2018 HFE, were collected. All continuous stage, discharge, water-quality, and acoustical suspended-sediment data have been uploaded to, and are available at, the U.S. Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC) website (www.gcmrc.gov or https://www.usgs.gov/centers/sbsc/gcmrc/). Unlike in previous years where, by late November, we had completed the processing of 95% of all suspended-sediment samples collected the previous fiscal year, processing of the suspended-sediment samples collected during FY 2019 data is only ~70% complete. This aspect of the project is still behind schedule as a result of the January 2019 government shutdown and an unrelated several-month delay in hiring replacement laboratory technicians by the USGS.

2) Maintenance and continued updating of the database and website can be accessed at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. All stage, discharge, water-quality (water temperature, specific conductance, turbidity, dissolved oxygen), suspended-sediment, and bed-sediment data collected at the active and inactive monitoring stations on the Colorado River and its tributaries are posted at this website. User-interactive tools at this website allow visualization and downloading of these data and the construction of sand budgets and duration curves.

3) Two peer-reviewed interpretive journal articles were published, three abstracts were submitted, and oral presentations given at professional scientific meetings during FY 2019. See products list below. In addition to these products, work progressed during 2019 on several manuscripts under the FY 2018–20 Triennial Work Plan. One entitled "What grain size reveals about suspended-sand transport in the Colorado River in Grand Canyon," by David M. Rubin, Daniel Buscombe, Scott A. Wright, David J. Topping, Paul E. Grams, John C. Schmidt, Joseph E. Hazel, Jr., and Matthew Kaplinski has been through review at the *Journal of Geophysical Research–Earth Surface*, revised, and resubmitted. Two other manuscripts are nearing completion and will be submitted for peer review this winter. These include: "Peak-stage indicators of Colorado River floods in Grand Canyon National Park" by Thomas A. Sabol, Ronald E. Griffiths, David J. Topping, Erich R. Mueller, Robert B. Tusso, and Joseph E. Hazel, Jr. (to be submitted as a USGS Open-File Report), and "Effects of a dam and episodic tributary resupply on sand transport and storage in a supply-limited river," by David J. Topping, Ronald E. Griffiths, Paul E. Grams, David M. Rubin, and others (to be submitted to the *Journal of Geophysical Research–Earth Surface*).

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Grain-size controls on sand storage in rivers	Dec 2018	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—Abstract EP31C-2358: Washington, D.C., Dec. 10-14, 2019, 2018 Fall Meeting, AGU.
Presentation	Geomorphic change and biogeomorphic feedbacks in a dryland river: The Little Colorado River, Arizona, USA	Sept 2019	Dean, D.J., and Topping, D.J., 2019, Geomorphic change and biogeomorphic feedbacks in a dryland river—abstract: The Little Colorado River, Arizona, USA: Phoenix, Ariz., September 2019, Geological Society of America Abstracts with Programs, v. 51, no. 5, https://doi.org/10.1130/abs/2019AM-339900.
Presentation	Geomorphic change, biogeomorphic feedbacks, and the downstream transformation of floodwaves in the Little Colorado River, Arizona, USA	Sept 2019	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.,September 9-12, 2019, 15th Biennial Conference of Science & Management on the Colorado Plateau and Southwest Region, High Country Conference Center, Northern Arizona University.
Journal article	How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise	Jan 2019	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, no. 1, p. 160-178, https://doi.org/10.1002/esp.4489.
Journal article	Geomorphic change and biogeomorphic feedbacks in a dryland river: The Little Colorado River, Arizona, USA	April 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, no. 11-12, p. 1920- 1942, https://doi.org/10.1130/B35047.1.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Web application	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.	hourly	Online realtime database: http://waterdata.usgs.gov/nwis
Web application	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 month	Online database and web-based applications: http://www.gcmrc.gov/discharge_qw_sediment/ and http://cida.usgs.gov/gcmrc/discharge_qw_sediment/

Project B: Sandbar and Sediment Storage Monitoring and Research

Project Lead	Paul Grams	**Principal Investigator(s)** (PI)	Paul Grams, USGS, GCMRC Keith Kohl, USGS, GCMRC Robert Tusso, USGS, GCMRC Robert Ross, USGS, GCMRC Daniel Buscombe, NAU Matt Kaplinski, NAU Joe Hazel, NAU Erich Mueller, SUU
Email	pgrams@usgs.gov		
Telephone	(928) 556-7385		

SUMMARY

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. Outcomes from this project will be used to evaluate the effectiveness of the HFE protocol included in the 2016 Long-Term Experimental and Management Plan Record of Decision with respect to sandbar condition.

The list of products, below, is cumulative for the fiscal year (FY) 2018-2020 workplan and includes three recurring data products, eight products completed in FY 2019 and FY 2010 products that were completed in FY 2018. In addition to those listed products, ten presentations were made involving project investigators at professional meetings.

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

Sandbar Monitoring and Response to High-Flow Experiments

Sandbar monitoring data were collected in October 2018, processed, and reported at the annual reporting meeting in March 2019. Images from the remote cameras were retrieved in October 2018, April 2019, and October 2019. As of the end of FY 2019, five HFEs have been conducted, all under sand-enriched conditions, since the HFE Protocol was initiated in 2012. Those HFEs occurred in November of 2012, 2013, 2014, 2016, and 2018. In each case, sandbar building results were generally consistent with the results from previous HFEs. All HFEs resulted in substantial deposition at all sandbar types (see Mueller and others, 2018 for description of sandbar types). Deposition was followed by erosion of about half the new deposits within six months, which is also consistent with the response to previous HFEs. Response immediately after the 2018 HFE based on digital camera images of sandbars from Lees Ferry to Diamond

Creek indicated that there was a substantial gain (deposition) for 27 sandbars (66% of sites), no substantial change for nine sandbars (22% of sites), and substantial loss (erosion) for five sandbars (12% of sites) (Figure 1). The HFE deposits typically begin eroding immediately following each HFE and the bulk of the newly deposited sand persists for approximately 6 to 12 months. Annual topographic surveys of sandbars were conducted between September 26 and October 12, 2018. Data from these surveys indicate that there has been some net increase in the size of reattachment sandbars since the beginning of the HFE protocol in 2012 (Figure 2). 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, 2018). Although HFEs do not prevent vegetation encroachment, HFEs do provide increases in campsite area—even if those increases are temporary. Results from the October 2019 annual sandbar survey ,that show sandbar conditions 11 months after the most recent HFE in November 2018, will be presented at the Annual Reporting Meeting in January 2020.

Developments in Sandbar Data Processing and Public Database

FY 2019 was the second year of implementing the new workflow and database for processing, analyzing, storing, and disseminating the sandbar monitoring data. The new 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 at (www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar). The database stores the results of over 1,700 individual topographic and bathymetric surveys that have been completed at the collection of 45 long-term monitoring sites.

Analysis of Remote Camera Images

In FY 2019, additional progress was made on the effort to automate analysis of the remote camera images of sandbars. This has included the development of machine learning software for automated segmenting of the sandbars from the images (Buscombe and Ritchie, 2018) and identification of metrics for sandbar size that can be easily extracted from the remote camera images and correlated with the annual measurements of sandbar volume. In FY 2019, additional ground control points were collected at most long-term sandbar sites to finalize rectifications for all sites and compute reprojection errors. Rectification is the perspective transformation of the image into a planform image in a projected coordinate system, which enables sandbar areas to be estimated. The reprojection errors are horizontal errors in meters in Eastings and Northings and will be factored into final uncertainties of sandbar area

estimates. The software for automated segmenting of the sandbars has been refined and improved by correcting a model bias that caused segmentation errors to increase at sites further from the camera. Additionally, the frequency of sandbar mass failures, as revealed in the remote camera period of record for each site, has been documented. This analysis is part of an ongoing project into why some sandbars exhibit this behavior and others do not, with implications for both understanding and predicting sandbar dynamics as well as boater and camper safety.

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

Data Collection

In FY 2019, data were collected to map changes in riverbed sand storage in Lower Marble Canyon and eastern Grand Canyon. These data were collected on a 21-day river trip in April 2019. This trip involved 151 multibeam sonar surveys and 126 terrestrial surveys. Over 2,600 images were collected to characterize the composition and grain size of riverbed sediment. Data were also collected with frequency-modulating sonar to enable estimates of riverbed sand thickness. Processing of these data is underway by cooperators at Northern Arizona University.

Data Processing and Reporting

In FY 2019, progress was made on processing of data collected in the previous work plan. The topographic and bathymetric data collected in Glen Canyon (between Glen Canyon Dam and Lees Ferry) were integrated with photogrammetrically-derived elevations to produce a complete high-resolution digital elevation model for this segment. These data are currently available upon request and may be viewed online (grandcanyon.usgs.gov/portal/home). Data releases for Glen Canyon and previous channel mapping efforts from 2011 to 2016 are planned in FY 2020.

Grams and others (2018b) 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. 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). In FY 2019, analysis was completed for two additional repeat mapping data sets. These 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). These findings will be presented at the Annual Reporting Meeting in January 2020.

Advances in Bedload Sediment Transport and Bed Sediment Classification

In FY 2019, several manuscripts have been prepared and submitted to journals on the topic of refining bedload sediment transport estimates in Grand Canyon. The three papers have examined different aspects of the problems of data processing, collection and modeling of bedload. Leary and Buscombe (2019) estimated the error associated with using a time-series of bed elevation changes at a point from a singlebeam sonar with a 4D dataset collected with a multibeam sonar, concluding that doing so introduces unacceptable error due to the ambiguity of migrating dune length and period. Ashley and others (2019) developed a Bayesian framework for estimating bedload transport at each long-term sediment monitoring gage. The new model, based on theory developed by Rubin and Topping (2001), 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 (2019) have developed a new model for predicting bedload flux based on dune geometry and shear stress. We are now presented with a viable opportunity to estimate 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. In February 2019 we collected another 4D multibeam bed elevation and ADCP dataset from the vicinity of the Diamond Creek gage. To date, we have collected seven datasets such as these for the purposes of better estimating bedload transport at different flows using dune tracking; five at the Diamond Creek gage, and one each at 30-mile and 166-mile gages. We plan to issue a USGS data release in FY 2020.

Up until FY 2019, all bed sediment classification used data collected using a Reson 7125 system, and in FY 2019 we also made progress toward a similar bed sediment classification for the data collected by the Norbit multibeam system. Laboratory measurements were collected using the Norbit that help us to acoustically constrain estimates of riverbed substrates and submerged aquatic vegetation. We are in the beginning stages of developing a new software that will incorporate this new information into the existing acoustic processing codes, and enable us to estimate and merge substrate maps from both the Reson and Norbit acoustic data. In FY 2019, our in-house sidescan sonar processing software (PyHum) has been updated to Python 3 and upgraded with new features. Additionally, we switched hydrographic data collection software; a major undertaking that will make backscatter data processing less cumbersome and more accurate.

Control Network and Survey Support (B.3.)

There was no logistics funding in FY 2019 for operations to advance survey control into new regions of the Colorado River through Grand Canyon. Survey control is adequate for mapping channel bathymetry in all segments of Grand Canyon, except for portions of the segment between Bright Angel Creek and National Canyon. One additional control trip is needed to prepare for mapping that segment in the FY 2021-23 work plan. However, logistics funding for that trip is not currently in the FY 2020 budget.

In FY 2019, we mapped what had previously been two reaches and two river trips within the bounds of a single, 18-day river trip. Mapping efforts between Fence Fault at river mile 29 to Bright Angel Creek at river mile 88 were accomplished in April 2019 and entailed measurements from 121 control stations. These 121 stations were used to position 176 bathymetric shore station instruments and over 35,000 topographic points. Additionally, in October 2019, 68 control stations were occupied with total stations for sandbar monitoring. The control network was also referenced for terrestrial lidar point clouds at ten sites where aeolian sand transport was modeled and at 15 sites where historical aerial imagery was orthorectified to determine area and volume of popular sandbars in 1983.

The river primary control network has been processed and adjusted through National Geodetic Survey bluebooking protocols and computations providing an independent check of the network which had been developed through proprietary software. The Pages and Adjust software used to compute the National Spatial Reference System are open-source and support improved transparency of computation methods. Positions referencing NAD83(2011) rim station control differ from those referencing active CORS and positioned in ITRF 2014 by < 4 cm in both horizontal and vertical components (at 95% confidence). The results verify that the control stations used for channel mapping have high-accuracy positions on a global datum.

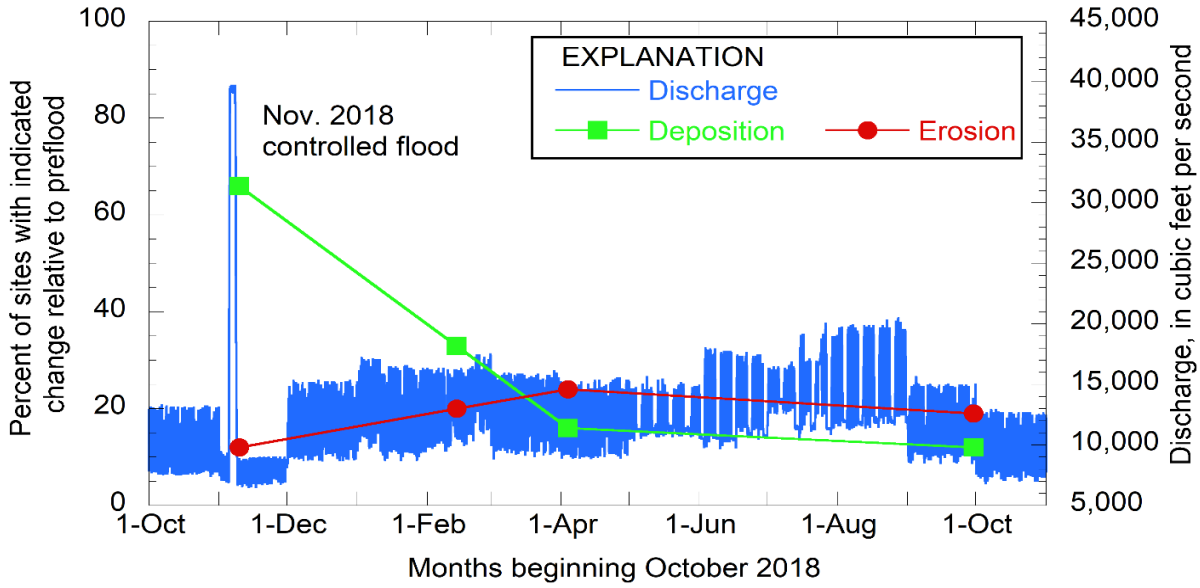


Figure 1. Percent of 45 monitored sandbar sites with deposition (green squares) or erosion (red circles) based on visual estimates of change in sandbar size in remote-camera images from monitoring sites along the Colorado River in Grand Canyon National Park, Arizona, following the November 2016 HFE and Colorado River discharge at Lees Ferry, Arizona (blue line) in cubic feet per second from October 1, 2018 to November 1, 2019. Figure is from Grams and others (2018a).

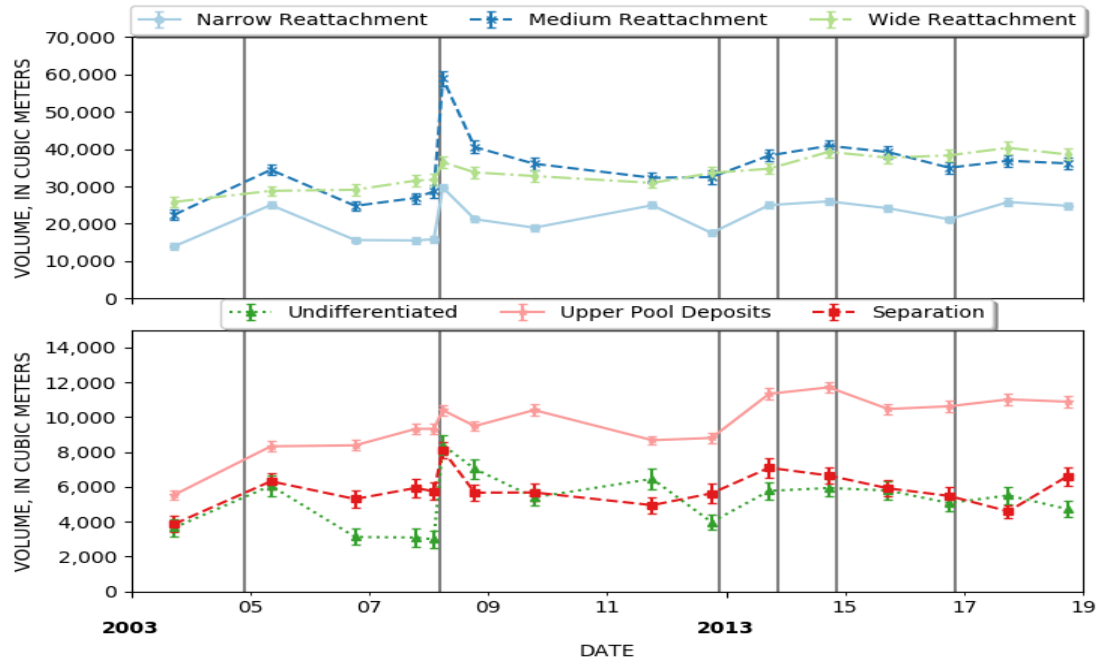


Figure 2. Sandbar volume (m^3) at long-term monitoring sites along the Colorado River in Grand Canyon National Park, Arizona by sandbar type from 1990 through October 2018. Group 1a, 1b, and 1c are unvegetated, moderately vegetated and heavily vegetated reattachment bars, respectively (Mueller and others, 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 and dashed lines are power-plant capacity releases. Modified from Mueller and others (2018).

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Project B.2: Report on automated methods for substrate classification	March 2018	Buscombe, D., Grams, P.E., and Kaplinski, M.A., 2018, Probabilistic models of seafloor composition using multispectral acoustic backscatter: GeoHab 2018 Conference, R2Sonic Multispectral Backscatter Challenge, Santa Barbara, Calif., May 8, 2018, 1-29 p., online download available at https://www.r2sonic.com/geohab2018/.
Presentation	Project B.1: Extended abstract on the effects of HFEs on sandbars	March 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.
Presentation	Project B.1: Extended abstract on the effects of HFEs on sandbars	March 2019	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.
Journal article	Project B.1: Journal article on sandbar changes	Dec 2017	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.
Journal article	Project B.2: Journal article on automated methods for substrate classification	Mar 2018	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.
Journal article	Project B.2: Journal article on automated methods for image classification	Jun 2018	Buscombe, D., and Ritchie, A.C., 2018, Landscape classification with deep neural networks: Geosciences, v. 8, no. 7, article 244, p. 1-23, https://doi.org/10.3390/geosciences8070244.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Journal article	Project B.2 Journal article on automated methods for substrate classification	Sept 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.
Journal article	Project B.1 Journal article on causes of campsite area change	Sept 2018	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.
Journal article	Project B.1 Journal article on sand-area change	Sept 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.
Journal article	Project B.2 Journal article on long-term monitoring of sand storage	Oct 2018	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.
Journal article	Project B.2: Journal article on methods for measuring sediment grain size from images	Oct 2019	Buscombe, D., 2019, SediNet—A configurable deep learning model for mixed qualitative and quantitative optical granulometry: Earth Surface Processes and Landforms, https://doi.org/10.1002/esp.4760.
Journal article	Project B.2: Journal article on methods for measuring sand bedload transport	Oct 2019	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, https://doi.org/10.5194/esurf-2019-38.
USGS Scientific Investigations Report	Project B.1 Report on causes of campsite area change	Dec 2017	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.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
USGS Open-File Report	Project B.1 Report on use of remote camera images for sandbar monitoring	Jan 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.
USGS Data	Project B.1: Data from long-term sandbar monitoring sites	Jan 2019	To be presented at annual reporting meeting and www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/
USGS Photos	Project B.1: Images from remote camera monitoring of sandbars	Jan 2019	Website: www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/
GCRG Photos	Project B.1: Images from GCRG adopt-a-beach program	Jan 2019	Website: www.gcmrc.gov/sandbar or https://www.usgs.gov/apps/sandbar/
USGS Data	Project B.1: Data on causes of campsite area change	Sept 2018	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.
USGS Data	Project B.1: Data on sand-area change	Oct 2018	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.
USGS Data	Project B.1: Data on sand-area change	Oct 2018	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.
USGS Data	Project B.2: Computer code automated methods for substrate classification	Oct 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 C: Riparian Vegetation Monitoring and Research

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC
Email	jsankey@usgs.gov		Brad Butterfield, NAU
Telephone	(928) 556-7289		Emily Palmquist, USGS, GCMRC
			Laura Durning, NAU

SUMMARY

Goals and Objectives FY 2019

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).

Project Element C.1. Ground-Based Vegetation Monitoring

Regular monitoring of the native to nonnative plant species ratio, species richness, and overall location and types of vegetation that occur in the CRe is the best way to assess whether the resource goals for riparian vegetation are being met. There are more than 300 different riparian plant species in the CRe that range from annual species that are only a few centimeters tall to hundred-year-old trees over 20 m tall. Thus, riparian vegetation in the CRe is layered and complex and it is best practice to monitor on both annual and decadal-scale time scales to observe rapid changes such as shifts in wetland communities, as well as slower changes such as tree growth and mortality. An example of slower change is impacts of the herbivorous tamarisk beetle that are born out over many growing seasons. It is also important to sample at multiple spatial scales and geographic extents and to monitor locations along the entire length of the corridor since riparian vegetation communities change with distance downstream (Palmquist and others, 2018a). The different floristic communities located along the river may not respond similarly to dam operations. For example, conclusions based on data from Marble Canyon cannot be applied to western Grand Canyon (Palmquist and others, 2018a).

In this project element of the FY 2018-20 workplan, we conduct annual ground-based vegetation monitoring to address the following objectives:

C.1.1. Annually sample and summarize the status (composition and cover) of native and nonnative vascular plant species within the riparian zone of the Colorado River from GCD and to 240 river miles downstream of Lees Ferry;

C.1.2. At 5-year intervals, assess change in vegetation composition and cover in the riparian zone, as related to geomorphic setting and dam operations, particularly flow regime;

C.1.3. Use available data to assess the required frequency for ground-based monitoring (i.e., power analysis);

C.1.4. Collect data in a manner that can be used by multiple stakeholders and is compatible with the basin-wide monitoring programs overseen by the NPS's Northern Colorado Plateau Network Inventory and Monitoring program.

Riparian vegetation monitoring data was collected between August 5 and October 21, 2019 and included sites between river miles -15.5 and 240. Data were collected at a total of 103 randomly selected sites and 42 long-term monitoring sites (NAU sandbar monitoring sites). These data are currently being entered and error checked. Data from the previous five years are being analyzed for patterns and trends (Figure 1). This analysis is currently being prepared as a status and trends report (Butterfield and others, in prep).

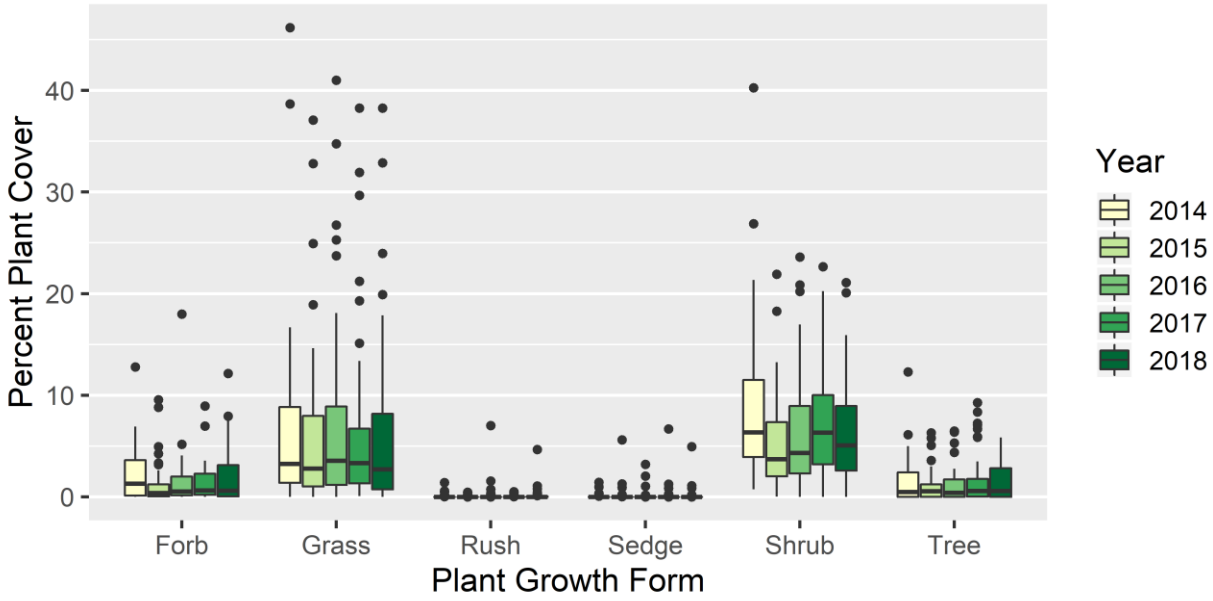


Figure 1. Percent foliar cover for six plant growth forms on annually surveyed sandbars by sample year. Median is indicated by the horizontal bar, the 25th and 75th percentiles are indicated by the box, whiskers extend to the most extreme data point that is not more than 1.5x the interquartile range, dots show outliers (Butterfield and others, in prep).

A comparison of riparian vegetation sampling methods was published in River Research and Applications (Palmquist and others, 2019). This method comparison assessed the strengths and weaknesses of the two main methods for sampling vegetation, ocular cover estimates and line-point intercept. 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. This comparison informed the sampling methods used in this program's long-term monitoring protocol (Palmquist and others, 2018b). This document is available at https://doi.org/10.1002/rra.3440.

The database that was developed to manage all current monitoring data following the published monitoring protocol (Palmquist and others, 2018b) is fully functional and in operation. We are currently extending its abilities to serve data to multiple outlets.

We are working toward assessing the required frequency for ground-based monitoring by determining the best methods for data analysis given the vegetation data structure and monitoring goals. Recently developed Bayesian models developed for the National Park Service Inventory & Monitoring program (Irvine and others, 2019) are being explored for their utility and practicability.

We continue to collaborate with the National Park Service's Northern Colorado Plateau Network Inventory and Monitoring – Big Rivers monitoring program. This collaboration allows us to maintain similar sampling methods and share ideas across the entire Colorado River Basin.

Project Element C.2. Imagery-based riparian vegetation monitoring at the landscape scale

In work completed prior to this FY 2018-20 workplan, landscape-scale remote sensing of riparian vegetation has been successfully used by GCMRC scientists to investigate several important contemporary environmental issues related to dam operations in the CRe. Specifically, we have: 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; Sankey and others, 2015b; Ralston and others, 2008), 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 (Sankey and others, 2016; Bedford and others, 2017). In the first year (FY 2018) of the current workplan (FY 2018-20), 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; Sankey and others, 2018).

In this project element of the FY 2018-20 workplan, we are leveraging those datasets and successful applications of landscape-scale remote sensing of riparian vegetation 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 FY 2019 to address each of the research and monitoring objectives. With respect to objective C.2.1, in FY 2019 we finalized our map (Durning and others, 2018; 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).

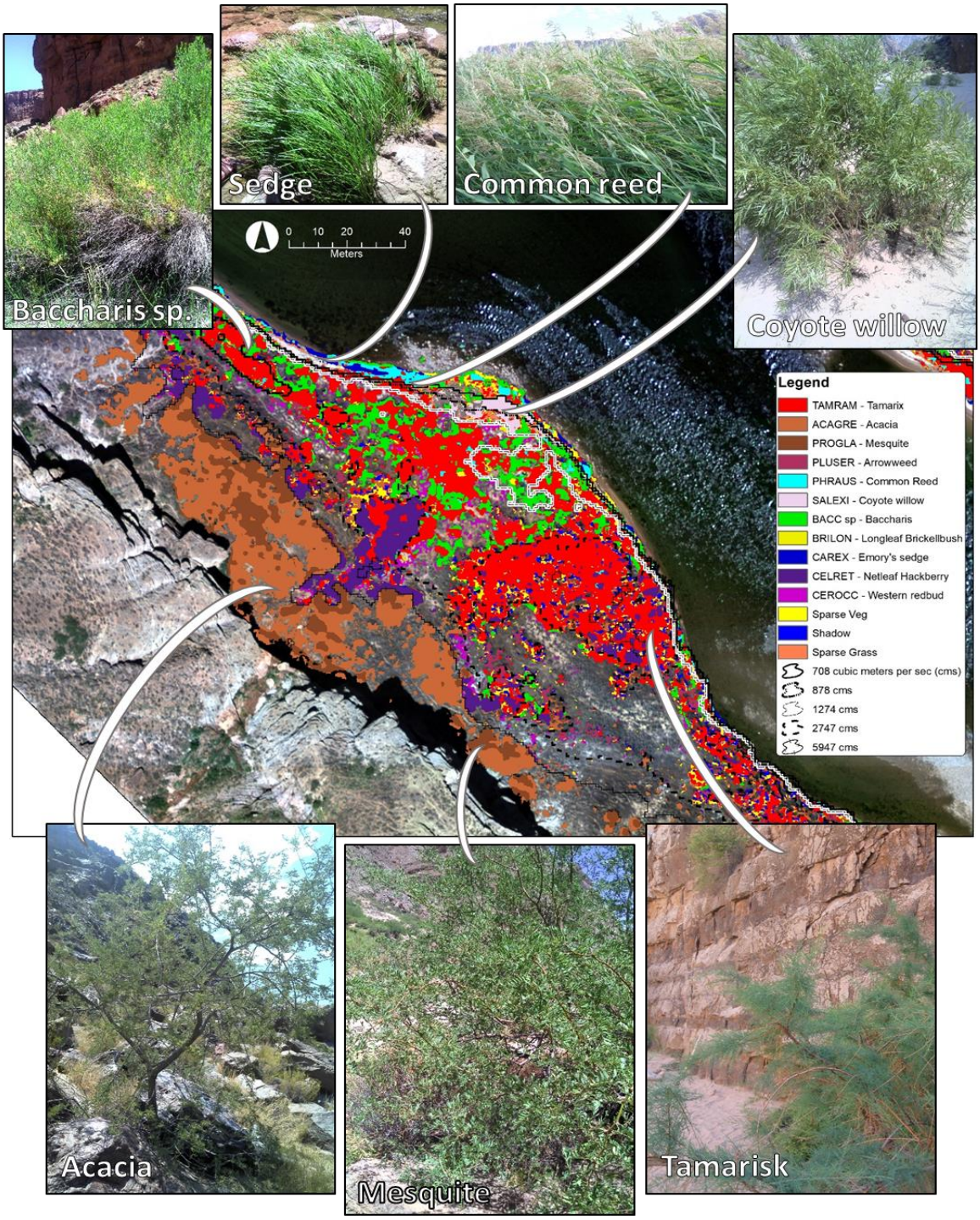


Figure 2. Example from the map of 2013 vegetation species classification by Durning and others (2018), with photos of dominant species. The map extends from Glen Canyon Dam to Lake Mead and is the highest resolution and most current map of riparian vegetation for the Colorado River ecosystem. The area displayed is river-right below Saddle Canyon (river kilometers from Lees Ferry, 77.6). Plant species codes are as follows: TAMRAM (*Tamarix ramosissima x chinensis*), ACAGRE (*Senegalia greggii*), PROGLA (*Prosopis glandulosa*), PLUSER (*Pluchea sericea*), PHRAUS (*Phragmites australis*), SALEXI (*Salix exigua*), BACC sp. (*Baccharis* sp.), BRILON (*Brickellia longifolia*), CAREX (*Carex* spp.), CELRET (*Celtis laevigata*), CEROCC (*Cercis orbiculata*), Sparse Veg (sparse areas of vegetation with limited or no training data), Shadow (vegetation in or created shadows), Sparse Grass (sparse areas of grass vegetation).

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 also 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 to address the questions posed by objectives C.2.1 and C.2.2. We have three different outlets or deliverables for the results of these analyses.

First, we delivered a talk at the Fall 2018 Meeting of the American Geophysical Union titled "Flow Alteration, River Valley Morphology, and the Influence of Glen Canyon Dam on Sediment Availability along the Colorado River in Grand Canyon" in December 2018 which covered the preliminary results of our work on C.2.2 on the interactions between riparian vegetation and bare sand for different geomorphic settings and hydrologic zones of the riparian area of the river. Second, during FY 2019 those preliminary results were further developed into a peer-reviewed journal article that examines the historic dynamics and future trajectory of riparian vegetation and bare unvegetated sand along the Colorado River in Grand Canyon. We originally intended to publish this work as a short technical paper in the proceedings of the Federal Interagency Sedimentation and Hydrologic Modeling Conference convened in June, 2019. However, we instead decided to develop the study into a full research article that we will submit to a peer-reviewed journal in FY 2020. Third, we have an additional manuscript in preparation which we plan to submit to a peer-reviewed journal in FY 2020 with a working title "A landscape scale evaluation of the Grand Canyon corridor's riparian vegetation composition and encroachment using remotely sensed imagery".

The report details our work on objectives C.2.1 and C.2.2 using the Durning and others (2018) and Sankey and others (2018) datasets to answer these questions:

- What vegetation species occur and at what proportions within the different geomorphic units and hydrologic zones of the riparian area? (see Figure 3);
- What riparian species are most responsible for riparian vegetation encroachment onto bare sand? (see Figure 4);
- What riparian species are most commonly subjected to burial by river sand? (see Figure 4).

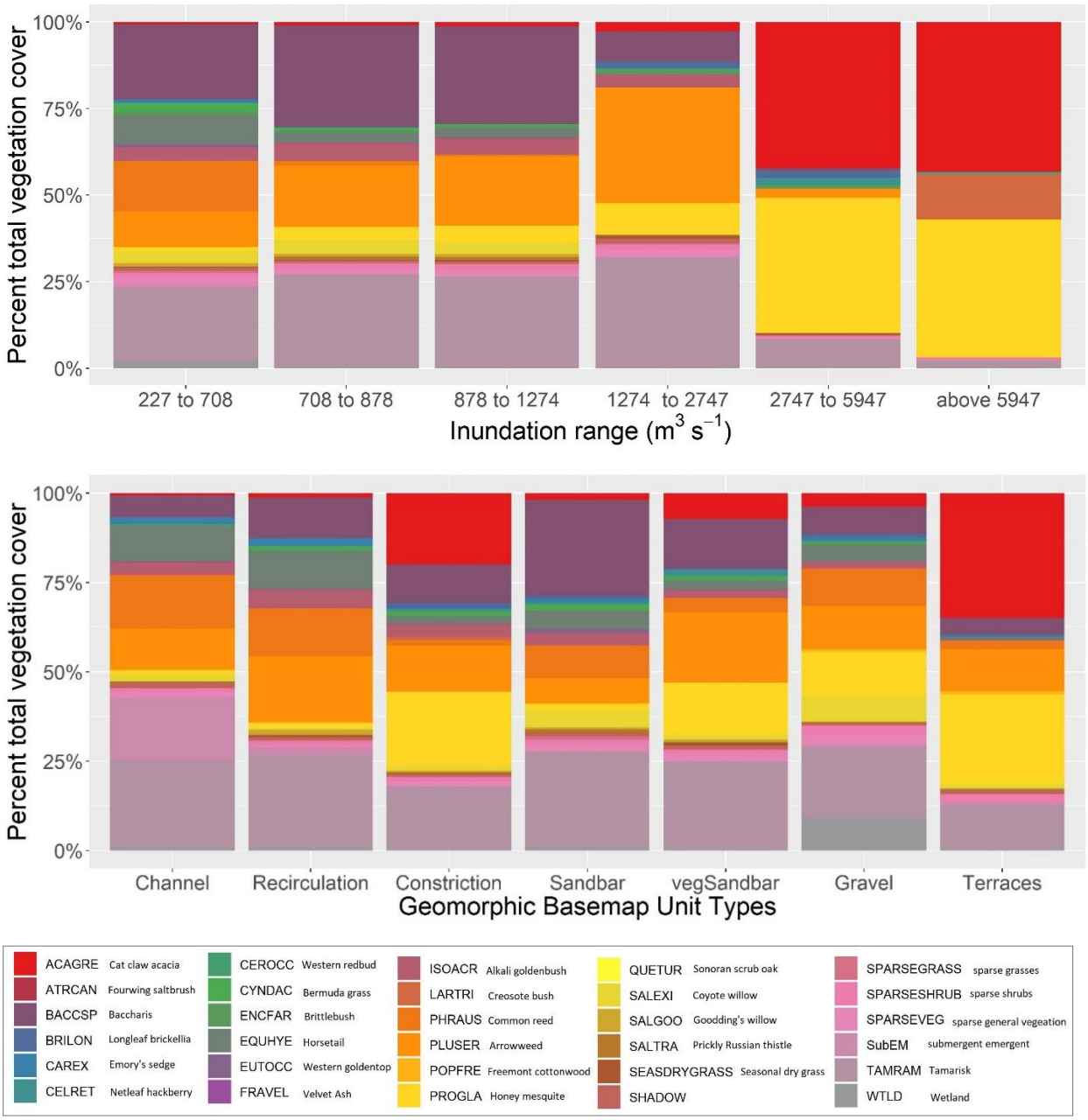


Figure 3. Riparian species composition from Lees Ferry to Diamond Creek based on Durning and others (2018) analysis of the May 2013 aerial overflight imagery. The top panel shows composition by hydrologic flow zone. The bottom panel shows composition for aggregated geomorphic units. Preliminary results from a manuscript in preparation; please do not cite.

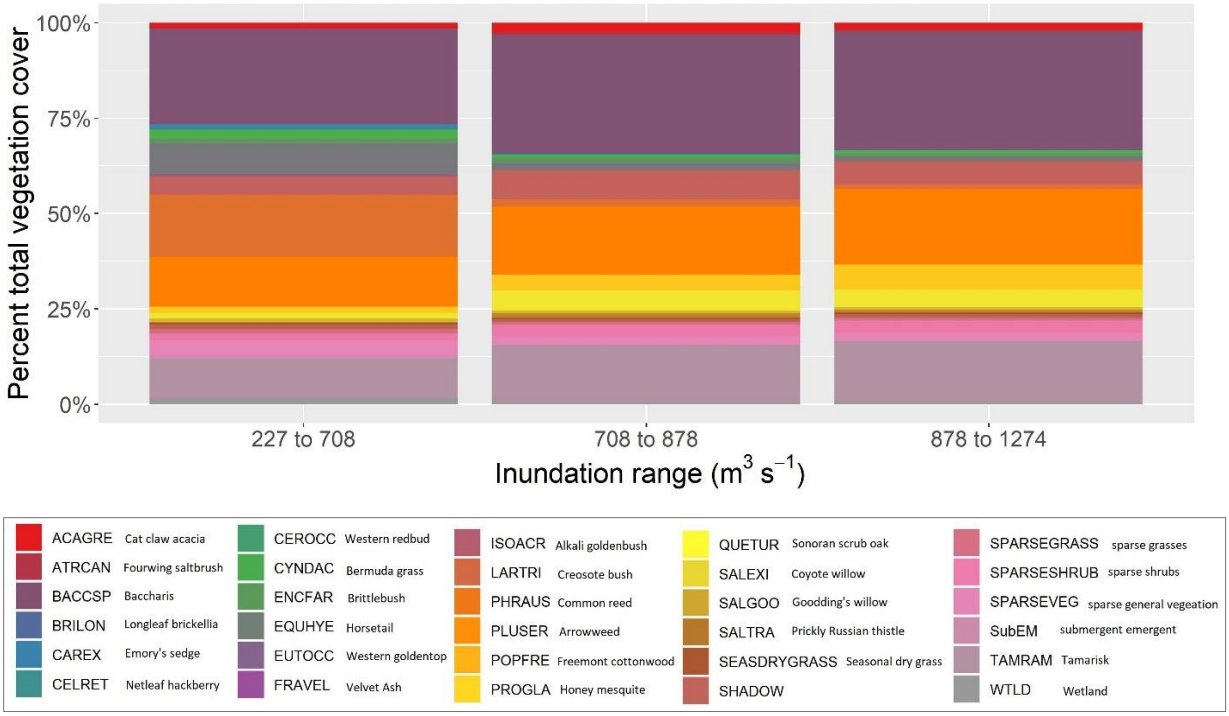


Figure 4. Species composition for three different modeled hydrologic zones on sandbars and other geomorphic surfaces where vegetation occurred in the 2002 overflight imagery, that was subsequently buried by Colorado River sand in the 2009 overflight imagery, and then riparian vegetation re-emerged and encroached as of the 2013 overflight imagery. The analysis was conducted from Lees Ferry to Diamond Creek using the data of Durning and others (2018). Preliminary results from a manuscript in preparation; please do not cite.

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 workplan. 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 planned for the last year of the FY 2018-20 workplan, and thus we will provide more information about this work as it progresses in future annual reports.

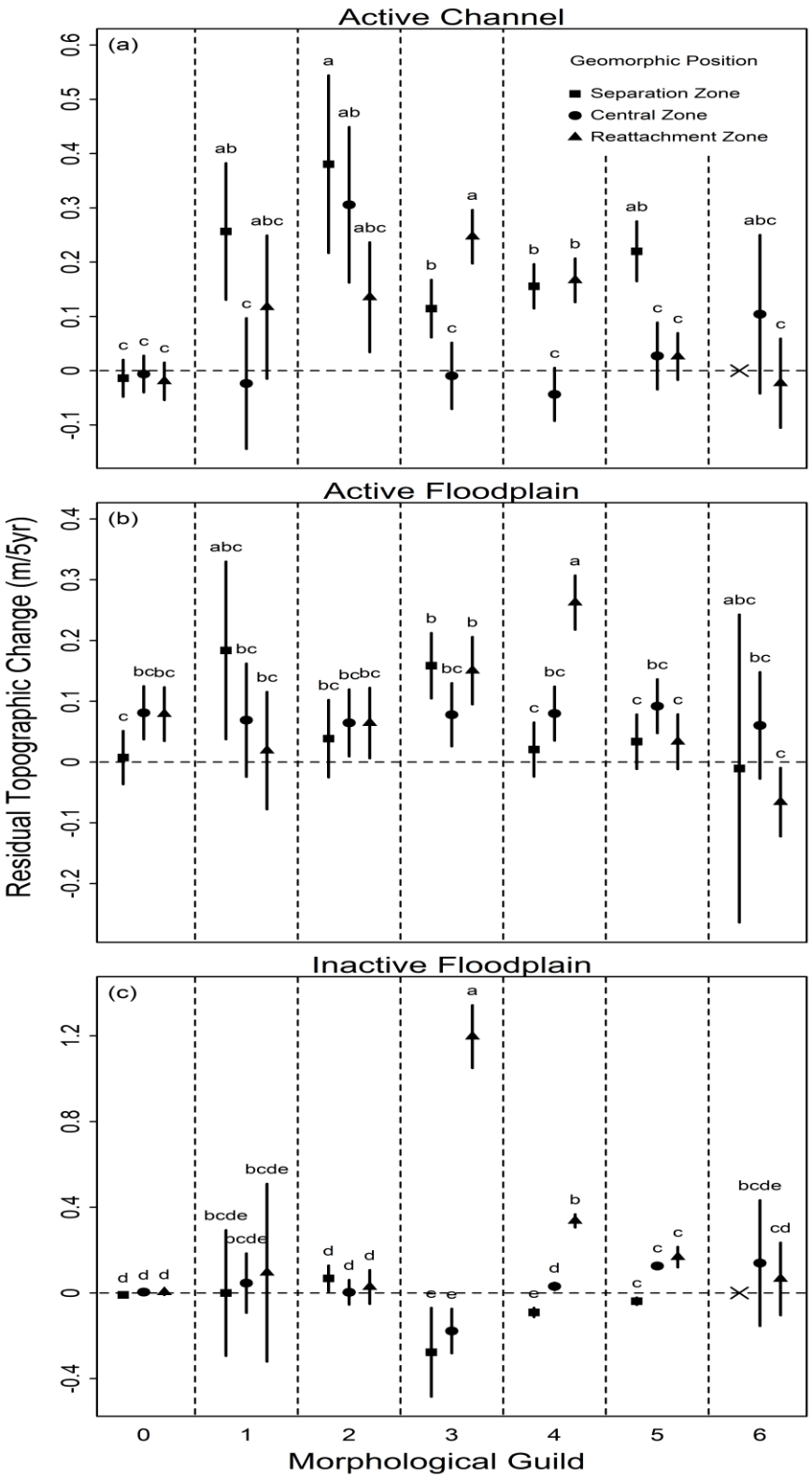


Figure 5. Deposition and erosion of sandbars as a function of hydrological regime (panels a-c), plant morphological guild (x-axis) and geomorphic position (symbols).

Project Element C.3. Vegetation Responses to LTEMP Flow Scenarios

Predictive models of riparian vegetation change in response to Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) flow scenarios can inform stakeholders about the potential influences of daily flows and alternative flows outlined in the LTEMP Record of Decision (ROD; e.g., trout management flows, spring high flow events, bug flows, equalization flows) on this resource of concern. This element will utilize existing vegetation data (from Elements C.1 and C.2) and flow data integrated with flow-response vegetation guilds to examine the influence of flow scenarios on species distributions and potential community change. The modeling done for the LTEMP EIS identified likely outcomes for plant community states, but at a basic level of presence or absence and expansion or contraction. The new modeling approaches provide more detail, potentially about specific species of interest to stakeholders, and will result in a better understanding of how dam operations change vegetation. In FY 2018 we published initial models that identified interactive effects of climate and flow regime on vegetation composition (Butterfield and others, 2018). These models were further applied to projections of changes in bare sand area throughout the canyon (see Element C.2 above).

In FY 2019 we have developed two new lines of inquiry that will improve our predictive models based on:

1. An understanding of vegetation feedbacks on sand deposition and erosion, and
2. Extending vegetation habitat prediction beyond the observed hydrological regime within the CRe and improve predictions of species sensitivity to hydrological and climatic variability.

To this first objective, we have submitted a manuscript to River Research and Applications (Butterfield and others, in review) titled “Associations between riparian plant morphological guilds and fluvial sediment dynamics along the regulated Colorado River in Grand Canyon.” This work merges the long-term sandbar monitoring digital elevation models with the 2013 vegetation classifications from the overflight to identify associations between plant effect guilds and changes in elevation, providing estimates of net deposition or erosion over the period from 2013-2018 that may be attributed to different plant groups. We found significant associations between vegetation and sandbar elevation change, and that these associations were very context-specific (Fig. 5). Specifically, there are strong interactions between hydrological regime, morphological guild, and geomorphic position, indicating that vegetation effects on sand dynamics are highly context-dependent but predictable. Low-statured rhizomatous and herbaceous species were highly effective at capturing sediment in the high velocity geomorphic settings, whereas tall herbs and large shrubs were more effective at capturing sediment in low-velocity geomorphic settings. These results provide clear predictions about the role of

vegetation in stabilizing sand, and which species/groups could be manipulated through direct vegetation management to achieve specific sand resource objectives. Furthermore, these feedbacks will be integrated into the next set of vegetation models to identify how successional processes (directional shifts from one type of vegetation to another over time) are likely to occur over time as plants continue to modify their local environment, and hence the hydrological conditions they experience.

The second objective of improving CRe vegetation predictions through use of a broader set of hydrological and climatic data is being achieved through integration of CRe and widespread data sources. The very narrow range of temporal variability in flow regime and climate for which we have detailed vegetation data in the CRe necessitates information on the same and similar species from other river systems. As a first step, we have developed a workflow for determining species hydrological and climatic niches using the National Hydrography Dataset Plus v.2 (NHDPlus).

The novel workflow that we have developed in the R statistical and geospatial language extracts monthly average river flow and velocity data from NHDPlus associated with species occurrence records in the Southwest Environmental Information Network. This is a novel integration and use of these existing datasets, so as a first step to assess the utility and validity of this approach, we have conducted an initial study of willow species' hydrological and climatic niches including two important CRe species, coyote willow (*Salix exigua*) and Gooding's willow (*Salix gooddingii*) (Fig. 6). Willows were chosen for this initial analysis because they represent a very diverse genus that has been well-documented in terms of where they occur, and because many willows are riparian obligates. Our initial results indicate that this method is quite valid, based on a strong concordance between the estimates of species' hydrological niches and knowledge of their ecology (Fig. 6).

These results confirm expectations that riparian species should occur more closely to streams than by chance, supporting our use of this geospatial approach. The middle panel of Fig. 6 demonstrates novel and important tradeoffs between willow species' temperature and riparian obligation niches, further informed by evolutionary relationships (phylogeny on the right). These kinds of data will help us to understand linked hydrological and climatic sensitivities of riparian vegetation in the CRe, providing a wider range of predictive ability under alternative flow and climate scenarios. A manuscript is in preparation. The next iteration of this modeling approach will be to develop range-wide models of all the common CRe riparian plant species to understand where they lie within their broader realized hydrological and climate niches. These models will greatly improve our ability to predict species' responses to on-going climate change, as well as to alternative flow scenarios, in ways that are impossible based on the narrow range of environmental variability in our empirical CRe datasets.

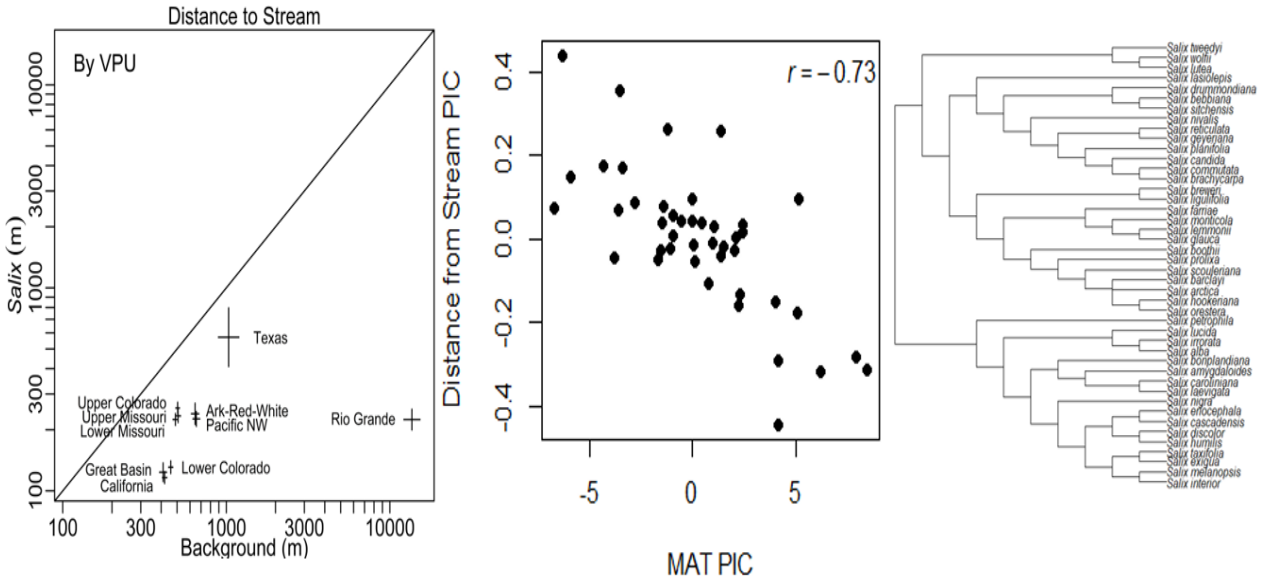


Figure 6. Preliminary results testing validity of workflow integrating west-wide hydrological, climate and species occurrence data to predict vegetation responses to hydrological and climate variability. The left panel shows the distribution of willow occurrences with respect to distance from streams, compared to a random background sample. The middle panel shows relationships between temperature (MAT PIC) and hydrological niches (Distance from Stream PIC). The right panel shows the phylogenetic relationships among willow species.

To support these statistical models which infer species' responses from correlations, we conducted a pilot experiment on physiological responses of arrowweed (*Pluchea sericea*) to flooding. The purpose of this experiment was to better understand the mechanisms of plant responses to dam operations under controlled conditions. Since field monitoring is limited by accessibility and the observed flow regime, we were interested in testing hypotheses in a greenhouse for a wider range of inundation depths and durations. We chose arrowweed for the pilot experiment, since it is a species of management interest. Cuttings collected from the along the Colorado River in Grand Canyon were flooded at different depths for 3 months over the summer of 2019. Data on growth, photosynthesis, rooting structure, and leaf traits were collected throughout and at the end of the study. These data are currently being processed. If this pilot study proves useful for understanding how plant species of interest respond to flow conditions, we will pursue options to continue these types of experiments with additional species and treatment conditions.

All of the above results will be presented at the January 2020 Annual Reporting Meeting. Results will be presented in the context of decision-support tool development based on exogenous (flow regime, climate and vegetation management) and endogenous (e.g. biotic feedbacks on sand) processes known to affect vegetation condition.

Project Element C.4. Vegetation Management Decision Support

GCMRC partners with NPS and Native American Tribes on the LTEMP Riparian Vegetation Mitigation Project C.7 Experimental Vegetation Treatment. GCMRC's roles and responsibilities in the project are:

- Project partners and scientific support
- Provide input to NPS and Tribal partners on project design, site selection, methods for implementation and monitoring
- Provide scientific support via monitoring and/or research to evaluate vegetation management treatment outcomes, effectiveness, and success
- Provide objective advice on project efficiency and adaptive management
- Help manage project data while respecting Tribal data sensitivity
- Attend and participate in meetings.

In FY 2019, GCMRC scientists, under the guidance of element C.4 and Project D, helped to design pilot experimental vegetation management treatments that were implemented by the National Park Service during a field campaign via river trip in April 2019. GCMRC's efforts in experimental vegetation removal treatments on campsites, sandbars, and associated archaeological sites are described in detail in the Project D annual report in this document and are not discussed further here.

In cooperation with the NPS, GCMRC scientists have conducted an assessment of genetic structure and differentiation of cottonwood (*Populus fremontii*), Goodding's willow (*Salix gooddingii*), coyote willow (*Salix exigua*), and honey mesquite (*Prosopis glandulosa*) in the Grand Canyon region (laboratory work funded by Grand Canyon National Park). The results of this work are anticipated to inform the development of genetically appropriate planting materials for the LTEMP experimental vegetation management treatments. These analyses indicate that cottonwoods are genetically different across the Grand Canyon region, genetic differences are related to geographic patterns, and populations within Grand Canyon are very different than those outside of Grand Canyon. The other three species are less genetically different across Grand Canyon, but Goodding's willow exhibits some notable geographic differences. Coyote willow and honey mesquite, both common along the Colorado River, are characterized by extensive gene flow throughout the region. These results were presented at two regional conferences, the 2019 Riparian Restoration Conference hosted by River's Edge West and the 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region. A manuscript is in preparation with a working title of, "Genetic structure and gene flow in woody riparian plants is mediated by geographic patterns."

REFERENCES

Bedford, A., Sankey, T.T., Sankey, J.B., Durning, L.E., and Ralston, B.E., 2017, Remote sensing derived maps of tamarisk (2009) and beetle impacts (2013) along 412 km of the Colorado River in the Grand Canyon, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/F72B8X71.

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., Grams, P.E., Durning, L.E., Hazel, J.E., Jr., Palmquist, E.C., Ralston, B.E., and Sankey, J.B., *in review*, Associations between riparian plant morphological guilds and fluvial sediment dynamics along the regulated Colorado River in Grand Canyon: River Research and Applications.

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.

Butterfield, B.J., Palmquist, E.C., and Ralston, B.E., *in prep*, Five-year status and trends of riparian vegetation in Glen and Grand Canyons downstream of Glen Canyon Dam: U.S. Geological Survey Open-File Report.

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.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, J.B., 2017a, Water classification of the Colorado River corridor, Grand Canyon, Arizona, 2013—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7PZ5799.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, T.T., 2017b, Riparian vegetation classification of the Colorado River corridor, Grand Canyon, Arizona, 2013—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7K64GJF.

Durning, L.E., Sankey, J.B., Davis, P.A., and Sankey, T.T., 2016, Four-band image mosaic of the Colorado River corridor downstream of Glen Canyon Dam in Arizona, derived from the May 2013 airborne image acquisition: U.S. Geological Survey Data Series 1027, https://doi.org/10.3133/ds1027.

Irvine, K.M., Wright, W.J., Shanahan, E.K., and Rodhouse, T.J., 2019, Cohesive framework for modelling plant cover class data: Methods in Ecology and Evolution, v. 10, no. 10, p. 1749-1760, https://doi.org/10.1111/2041-210X.13262.

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.

Palmquist, E.C., Ralston, B.E., Merritt, D.M., and Shafroth, P.B., 2018a, 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.

Palmquist, E.C., Ralston, B.E., Sarr, D.A., and Johnson, T.C., 2018b, 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.

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.

Ralston, B.E., Davis, P.A., Weber, R.M., and Rundall, J.M., 2008, A vegetation database for the Colorado River ecosystem from Glen Canyon Dam to the western boundary of Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008-1216, 37 p., https://pubs.usgs.gov/of/2008/1216/.

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.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015a, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, https://doi.org/10.1002/2015JG002991.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015b, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation—Data: U.S. Geological Survey data release, https://doi.org/10.5066/F7J67F0P.

Sankey, T.T., Sankey, J.B., Horne, R., and Bedford, A., 2016, Remote sensing of tamarisk biomass, insect herbivory, and defoliation—Novel methods in the Grand Canyon region, Arizona: Photogrammetric Engineering and Remote Sensing, v. 82, no. 8, p. 645-652, https://doi.org/10.14358/PERS.82.8.645.

U.S. Department of 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.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Hydrological regime and climate interactively shape riparian vegetation composition along the Colorado River, Grand Canyon	July 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, at Natural Ecosystems as Benchmarks for Vegetation Science: Bozeman, Mont., July 22-27, 2018, International Association of Vegetation Scientists 61st Annual Symposium.
Presentation	Flow Alteration, River Valley Morphology, and the Influence of Glen Canyon Dam on Sediment Availability along the Colorado River in Grand Canyon	Dec 2018	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., Dec 10-14, 2018, American Geophysical Union Fall Meeting.
Presentation	Genetic structure and gene flow in woody riparian plants: Implications for restoration in the Grand Canyon	Feb 2019	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. Feb. 5-7, 2019, RiversEdge West Riparian Restoration Conference.
Presentation	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	Feb 2019	Sankey, T.T., Bedford, A., Sankey, J.B., Ralston, B., and Durning, L., 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, Arizona, Feb. 5-7, 2019, RiversEdge West Riparian Restoration Conference.
Presentation	Effects of HFEs on sandbar vegetation	March 2019	Butterfield, B.J., Sankey, J.B., Palmquist, E.C., Durning, L., 2019, Effects of HFEs on sandbar vegetation, Grand Canyon, Arizona—presentation: Phoenix, AZ., March 12, 2019, Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Riparian vegetation monitoring and research	March 2019	Butterfield, B.J., Sankey, J.B., Palmquist, E.C., Durning, L., 2019, Riparian vegetation monitoring and research, Grand Canyon, Arizona—presentation: Phoenix, Ariz., March 12, 2019, Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program.
Presentation	Landscape scale riparian corridor analysis using 2013 remotely sensed airborne data, Grand Canyon, Arizona	March 2019	Durning, L., Sankey, J.B., 2019, Landscape scale riparian corridor analysis using 2013 remotely sensed airborne data, Grand Canyon, Arizona—presentation: Phoenix, Ariz., March 12, 2019, Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program.
Presentation	Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA	March 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—presentation: Phoenix, Ariz., March 12, 2019, Annual Reporting Meeting to the Stakeholders of the Glen Canyon Dam Adaptive Management Program.
Presentation	Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA	Sept 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—presentation: Flagstaff, Ariz., September 9-12, 2019, 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region.
Presentation	Genetic structure and gene flow in woody riparian plants: A case study in the Grand Canyon	Sept 2019	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.
Journal article	Landscape-scale processes influence riparian plant composition along a regulated river	Jan 2018	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.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Journal article	Hydrological regime and climate interactively shape riparian vegetation composition along the Colorado River, Grand Canyon	June 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: Applied Vegetation Science, v. 21, no. 4, p. 572-583, https://doi.org/10.1111/avsc.12390.
Journal article	A comparison of riparian vegetation sampling methods along a large, regulated river	May 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.
USGS Techniques and Methods Report	Monitoring riparian vegetation composition and cover along the Colorado River downstream of Glen Canyon Dam	June 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	Riparian vegetation and environmental variables, Colorado River, 2014—Data	Oct 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.
USGS Data	Climate, hydrology and riparian vegetation composition data, Grand Canyon, Arizona	July 2018	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.
USGS Data	Riparian species vegetation classification data for the Colorado River within Grand Canyon derived from 2013 airborne imagery: U.S. Geological Survey data release	Jan 2019	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.

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

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

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 GCD Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) 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 (U.S. Department of Interior, 2016a). High-Flow Experiments (HFEs) are one component of the selected alternative that will be used to resupply sediment to sandbars in Marble and Grand Canyons, which in conjunction with targeted vegetation removal, is expected to resupply more sediment via wind transport to archaeological sites, depending on site-specific riparian vegetation and geomorphic conditions. However, HFEs have been shown to directly erode terraces that contain archaeological sites in Glen Canyon National Recreation Area (GLCA; East and others, 2016; U.S. Department of Interior, 2016a). HFEs have also been shown by Sankey and others (2018b) to rebuild or maintain sandbars that provide sand to resupply aeolian dunefields containing archaeological sites throughout Marble and Grand Canyons. Aeolian dunefields were resupplied with sand 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).

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 will be undertaken under the LTEMP Record of Decision (ROD; U.S. Department of the Interior, 2016b) through 2036. The data and analyses from this project will allow the GCDAMP to objectively evaluate whether and how these flow and non-flow actions directly affect cultural resources, vegetation, and sediment dynamics. It will also allow determination of how flow and non-flow actions will ultimately affect the long-term preservation of cultural resources and other culturally-valued and ecologically important landscape elements located within the river corridor downstream of GCD.

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 in 2019 are described below for each project element.

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

Summary of work completed in FY 2019

- Grand Canyon Monitoring and Research Center (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 GCMRC has specifically monitored for changes in geomorphic condition tied to dam-operations using lidar remote sensing and weather stations during the past decade. Grand Canyon staff implemented the proposed vegetation removal treatments at five sites during a field campaign via river trip conducted in April 2019. The work was carried out by NPS staff and tribal youth from the Ancestral Lands Conservation program. Dr. Sankey from GCMRC also 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 bullets below) immediately following the NPS trip in order to collect initial monitoring data for the vegetation removal treatments (Figure 1). Repeat monitoring in FY 2020 and later years will provide the data necessary to evaluate the outcome of the vegetation removal treatments (Figure 2).
- A field campaign to monitor changes in geomorphic condition tied to dam operations was conducted via river trip in May of 2019. Six 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 Canyons. The monitoring plan was shared with stakeholders in 2016 during the 2015-17 Triennial Work Plan (TWP), and again more recently with signatories of the Programmatic Agreement for Cultural Resources as part of the Historic Preservation Plan[1]. Five of the sites were those at which the NPS had conducted experimental vegetation removal treatments in April, 2019.
- Weather station data is important for interpreting monitoring data related to geomorphic effects of dam operations and vegetation management. Similar to past years, weather data were downloaded from six stations during field campaigns, one at Ferry Swale in Glen Canyon (river mile -11), one at Lees Ferry, and one at each of four Marble and Grand Canyon archaeological sites (e.g., Caster and others, 2014,

[1] The Programmatic Agreement for Cultural Resources is on file with the Bureau of Reclamation, Upper Colorado Region, Salt Lake City.

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. Several of the existing weather stations needed to be overhauled in 2019 to ensure data continuity. Weather station equipment was repaired and upgraded as necessary at existing stations, and a new weather station was installed at Soap Creek (river mile 10). Thus, a total of seven stations collected weather monitoring data during 2019 and those data will be retrieved during field campaigns in 2020.

- At three sites, stationary cameras took photographs up to four times per day to record information about the timing and nature of landscape change.
- All monitoring data acquired in 2019 were processed and archived at GCMRC.
- A report summarizing archaeological site monitoring data acquired from 2010 to2018 has been completed by project staff and is currently in external review with the NPS and USBR (U.S. Bureau of Reclamation). 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 2010-2018." It is anticipated that the report will be published in 2020 as a USGS Open-File Report once the review process is completed.
    - The report summarizes baseline data collected at 23 archaeological sites. The report also summarizes the geomorphic changes that have been documented at five sites with two or more lidar monitoring episodes between 2010 and 2018.
    - This report and the monitoring data contained therein will provide baseline data (see Figures 1 and 2 below) for evaluating the pilot experimental vegetation management treatments implemented by the National Park Service beginning in 2019 per the LTEMP EIS . The report contains baseline data acquired between 2010 and 2018 for four of the five pilot sites.
    - 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).

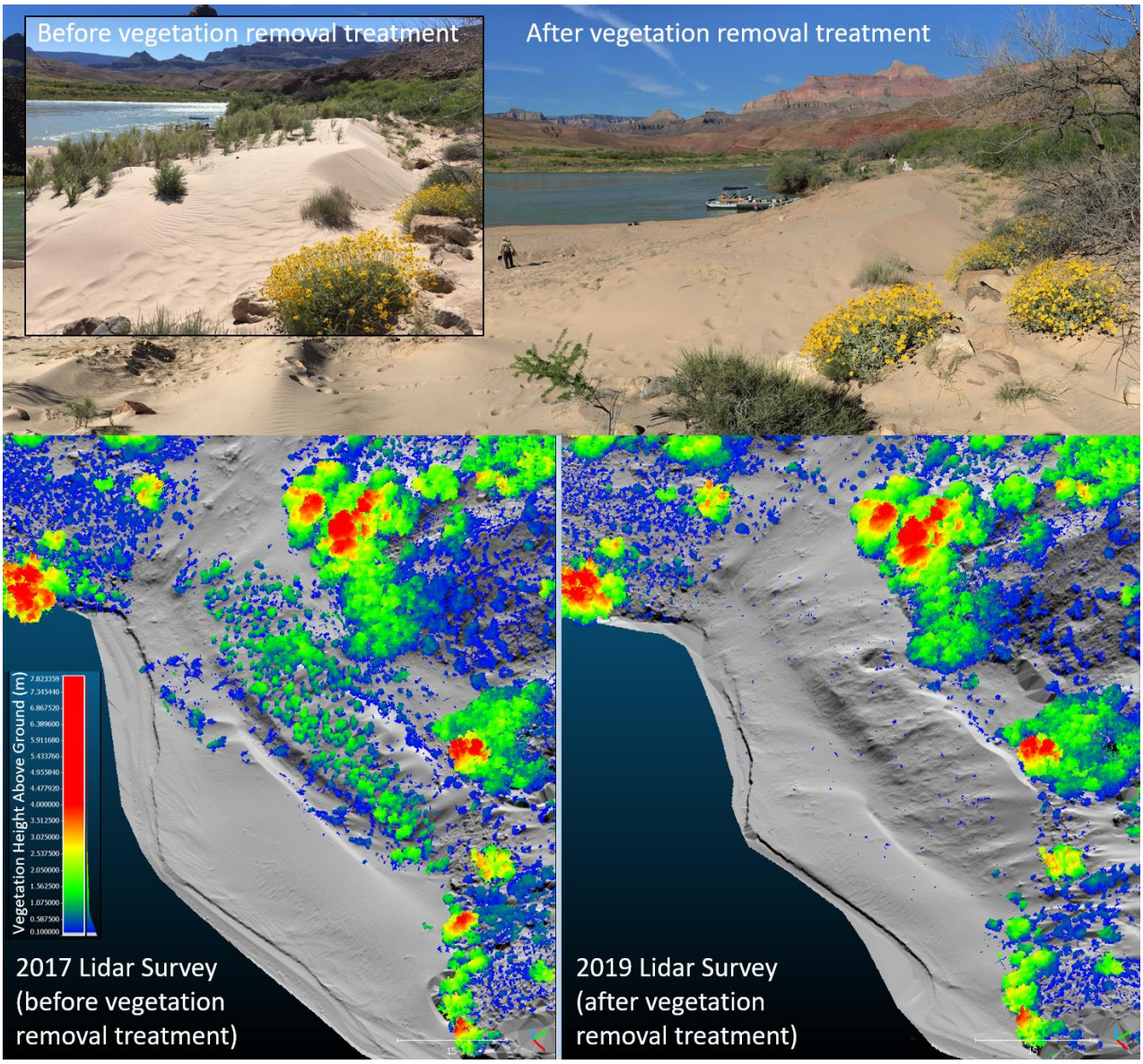


Figure 1. Photos and lidar survey data showing the vegetation removed by NPS during the experimental vegetation management treatment near archaeological site AZ:C13:0321. The treatment at this and other sites is intended to increase sediment storage at the sites by enhancing aeolian transport of Colorado River HFE sand 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, 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.

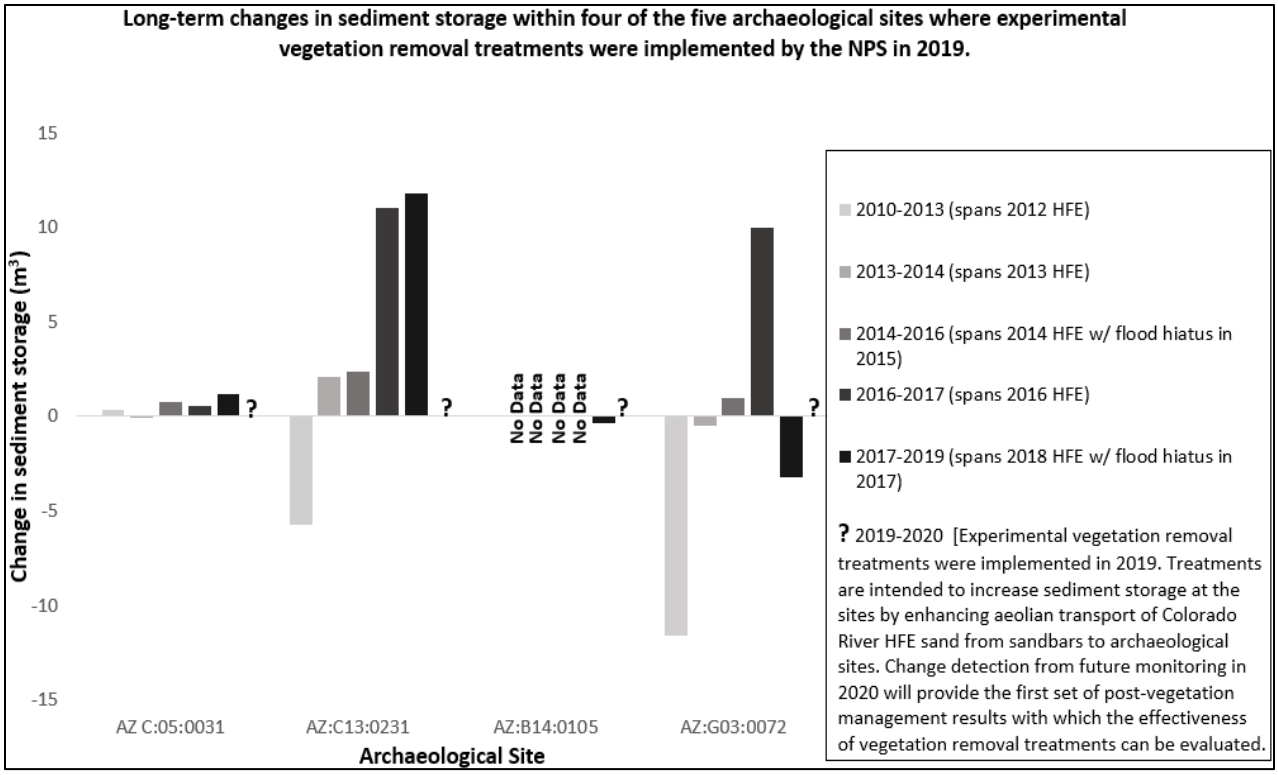


Figure 2. Results from long-term monitoring of changes in sediment storage from lidar surveys at four of the five archaeological sites where experimental vegetation removal treatments were implemented in April 2019 by the NPS. Treatments are intended to increase sediment storage at the sites by enhancing aeolian transport of Colorado River HFE sand from sandbars to archaeological sites. Change detection from future monitoring in 2020 will provide the first set of post-vegetation management results with which to evaluate the effectiveness of vegetation removal treatments in comparison to the baseline data shown in this figure.

Project Element D.2. Cultural Resources Synthesis to Inform Historic Preservation Plan

In the 2018-2020 TWP, 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, followed by a more in-depth exploration of existing monitoring photographs collected by the Grand Canyon National Park (GRCA) 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).

The synthesis report was completed in September 2018 and has 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.

In June 2019, an evaluation of the GRCA 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 GRCA 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 severely limits 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 particular 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 (Figure 3). This work builds upon earlier photographic-matching efforts initiated in 2015 during a previous phase of Project D (see Project 4 in the FY 2015-2017 TWP). 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, the collection of the photo-matches was accomplished with the aid of two unpaid volunteers (Figure 4). We plan to continue this photo-matching effort for at least one more field season in FY 2020.

Figure 3. Photographic match of lidar study site near river mile 122. Top view taken by an unknown member of the Weeden campsite survey project in July, 1973 (Weeden and others, 1975). Bottom view by A. H. Fairley, May 2019. Note the large area of open sand in 1973 that is now largely overgrown by vegetation.

Figure 4. Volunteer photographer Alan Fairley (left) and USGS emeritus ecologist Michael Scott (right) match a 1923 photograph taken by E.C. La Rue above Nankoweap Rapids. Photograph by Helen Fairley, May 2019.

REFERENCES

Caster, J.J., Dealy, T.P., Andrews, T., Fairley, H., East, A., and Sankey, J.B., 2014, Meteorological data for selected sites along the Colorado River corridor, Arizona, 2011-13: U.S. Geological Survey Open-File Report 2014-1247, 56 p., https://doi.org/10.3133/ofr20141247.

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.

Draut, A.E., 2012, Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA: Journal of Geophysical Research—Earth Surface, v. 117, no. F2, https://doi.org/10.1029/2011JF002329.

East, A.E., Collins, B.D., Sankey, J.B., Corbett, S.C., Fairley, H.C., and Caster, J.J., 2016, Conditions and processes affecting sand resources at archeological sites in the Colorado River corridor below Glen Canyon Dam, Arizona: U.S. Geological Survey Professional Paper 1825, 104 p., https://doi.org/10.3133/pp1825.

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.

Kintigh, K., Lipe, W., Altschul, J.H., and Urquhart, N.S., 2007, Legacy monitoring data review panel—unpublished report to the Grand Canyon Monitoring and Research Center: Legacy Monitoring Data Review Panel, 42 p. plus appendices, https://www.usbr.gov/uc/progact/amp/twg/2007-12-04-twg-meeting/Attach_10.pdf.

Sankey, J.B., Caster, J.J., Kasprak, A., and East, A.E., 2018a, 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., 2018b, 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.

Sankey, J.B., Ralston, B.E., Grams, P.E., Schmidt, J.C., and Cagney, L.E., 2015, Riparian vegetation, Colorado River, and climate—Five decades of spatiotemporal dynamics in the Grand Canyon with river regulation: Journal of Geophysical Research—Biogeosciences, v. 120, no. 8, p. 1532-1547, https://doi.org/10.1002/2015JG002991.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport—1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515-542, https://doi.org/10.1029/1999WR900285.

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

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

Weeden, H., Borden, F., Turner, B., Thompson, O.N., Strauss, C., and Johnson, R.R., 1975, Grand Canyon National park campsite inventory—unpublished Colorado River research report: National Park Service, submitted to Pennsylvania State University, contract no. CX 001-3-0061, 72 p.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Process and progress in monitoring surficial changes to archaeological sites within Grand Canyon river corridor	March 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: Phoenix, Ariz., March 12, 2019, Annual Reporting Meeting, Glen Canyon Dam Adaptive Management Program.
Presentation	The response of source-bordering aeolian dunefields to the 2012-2016 High-Flow Experiments of the Colorado River in Grand Canyon	March 2019	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: Phoenix, Ariz., March 13, 2019, Annual Reporting Meeting, Glen Canyon Dam Adaptive Management Program—High-Flow Experiment Workshop.
Presentation	“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	March 2019	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—Oral presentation Marble Canyon, Ariz., March 29, 2019, Grand Canyon River Guides Training Seminar.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Understanding dam effects on downstream archaeological resources—Lessons learned from three decades of research downstream from Glen Canyon Dam, Arizona	April 2019	Fairley, H.C., 2019, Understanding dam effects on downstream archaeological resources—Lessons learned from three decades of research downstream from Glen Canyon Dam, Arizona—Oral presentation: Albuquerque, New Mex., April 11, 2019, Society for American Archaeology Annual Meeting.
Presentation	Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the Colorado River in Grand Canyon	Dec 2019	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 Meeting.
Presentation	Integrating lidar and SfM data from ground-based, unmanned (UAV) and manned aerial platforms to estimate sediment budgets for aeolian dunefields	Dec 2019	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 Meeting.
Journal article	The effects of topographic surveying technique and data resolution on the detection and interpretation of geomorphic change	FY 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.
USGS Fact Sheet	Managing sand along the Colorado River to protect cultural sites downstream of Glen Canyon Dam	FY 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	River valley sediment connectivity data, Colorado River, Grand Canyon, Arizona: U.S. Geological Survey data release	FY 2019	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: Nutrients and Temperature as Ecosystem Drivers: Understanding Patterns, Establishing Links and Developing Predictive Tools for an Uncertain Future

Project Lead	Charles B. Yackulic	**Principal Investigator(s)** (PI)	Charles B. Yackulic, USGS, GCMRC Bridget Deemer, USGS, GCMRC Kimberly Dibble, USGS, GCMRC Michael Yard, USGS, GCMRC Theodore Kennedy, USGS, GCMRC David Ward, USGS, GCMRC
Email	cyackulic@usgs.gov		
Telephone	928-556-7379		

SUMMARY

Overview

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). Given the importance of nutrients and temperature as drivers of the aquatic ecosystem, it is important to understand their spatio-temporal patterns. The primary goals of this project are to: 1) identify processes that drive spatial and temporal variation in nutrients and temperature within the Colorado River Ecosystem (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).

During FY 2019, we improved the water temperature model currently used to make predictions in the CRe that 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. We also used a combination of historical data and new sampling to characterize the potential role of both dam management and Colorado River tributaries in influencing spatio-temporal patterns in mainstem nutrient availability. While long-term nutrient monitoring at Lees Ferry (river mile (RM) 0) shows a strong correspondence between nutrient availability in the reservoir outflow and in the Lees Ferry reach (Vernieu, 2009), the degree to which nutrient availability might change with outflow discharge and during an HFE is not well known. In addition, watershed disturbances such as wildfires have been linked to increased stream phosphorus (P) availability in other ecosystems (Emelko and others, 2016), but the potential for tributary fires to affect the CRe is not known. Finally, while

baseflow P concentrations in many tributaries to the Grand Canyon are not high enough to significantly affect nutrient budgets, preliminary sampling in FY 2018 suggests that storm-based P inputs from the Paria River may contribute significantly to the CRe P budget. During FY 2019 we expanded our capacity to measure P during storms in the Paria River. We also used aquatic insect light trap samples collected before and after a major fire in the Shinumo watershed to look for an increased P concentration in the CRe food base (measuring the total phosphorus content of *Diptera*). Finally, we sampled for several P species during the fall 2018 HFE and during the summer 2019 bug flows to look at variation in P concentrations coming from the Glen Canyon Dam outflow. Key findings were that HFEs can elevate downstream soluble reactive phosphorus (SRP) concentrations, the most bioavailable form of P. In addition, we report significant increase in the total phosphorus (TP) content of adult midges across a 50-mile reach of the Colorado river after the Galahad Fire in the Shinumo watershed, suggesting the capacity for a tributary fire to influence the P content of the CRe food base.

During FY 2019, we continued to make 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. Initial analysis suggests that SRP exerts an important control on GPP all the way down to RM 60. In addition, adjusted weekend water releases due to bug flows had measurable effects on riverine GPP, but the direction and magnitude of this effect varied by site throughout the river. In FY 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. However, we made significant progress in FY 2019 by conducting these experiments under 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 mud snails (*Potamopyrgus antipodarum*, hereafter "mud snails") to determine the effect of 10°C, 15°C, and 20°C treatments on GPP and mud snail growth. Side experiments included investigating the effect of mud snail grazing on GPP under the three temperature treatments and investigating whether native fishes (humpback chub, roundtail chub, flannelmouth sucker) consume mud snails. In 2019 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. We also established two permanent reaches with transects in Glen Canyon in June 2019 and took approximately 30,000 underwater images that will provide baseline information to assess future aquatic vegetation change over time.

While more progress was made in conceptually developing an ecosystem model in FY 2019 than in FY 2018, systematic underfunding across modeling projects (and in database entry) 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 and requests are made for work beyond that outlined in the approved workplan.

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

Objectives:

E.1.1. *Modify previous models for predicting CRe temperatures to reflect exponential (rather than linear) warming*

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. Temperature predictions were generated using a linear warming model, but this model overestimates Colorado River temperatures by ~2°C in western Grand Canyon (Figure 1). To provide better predictions, we modified the current linear model of water temperature (Walters and others, 2000; Wright and others, 2008) 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). The new model improved temperature predictions by decreasing residual error, with the largest prediction improvements in western Grand Canyon sites (Figure 1). We used this model to explore how changes in air temperature, discharge, and Lake Powell release temperatures may change water temperatures throughout the Grand Canyon.

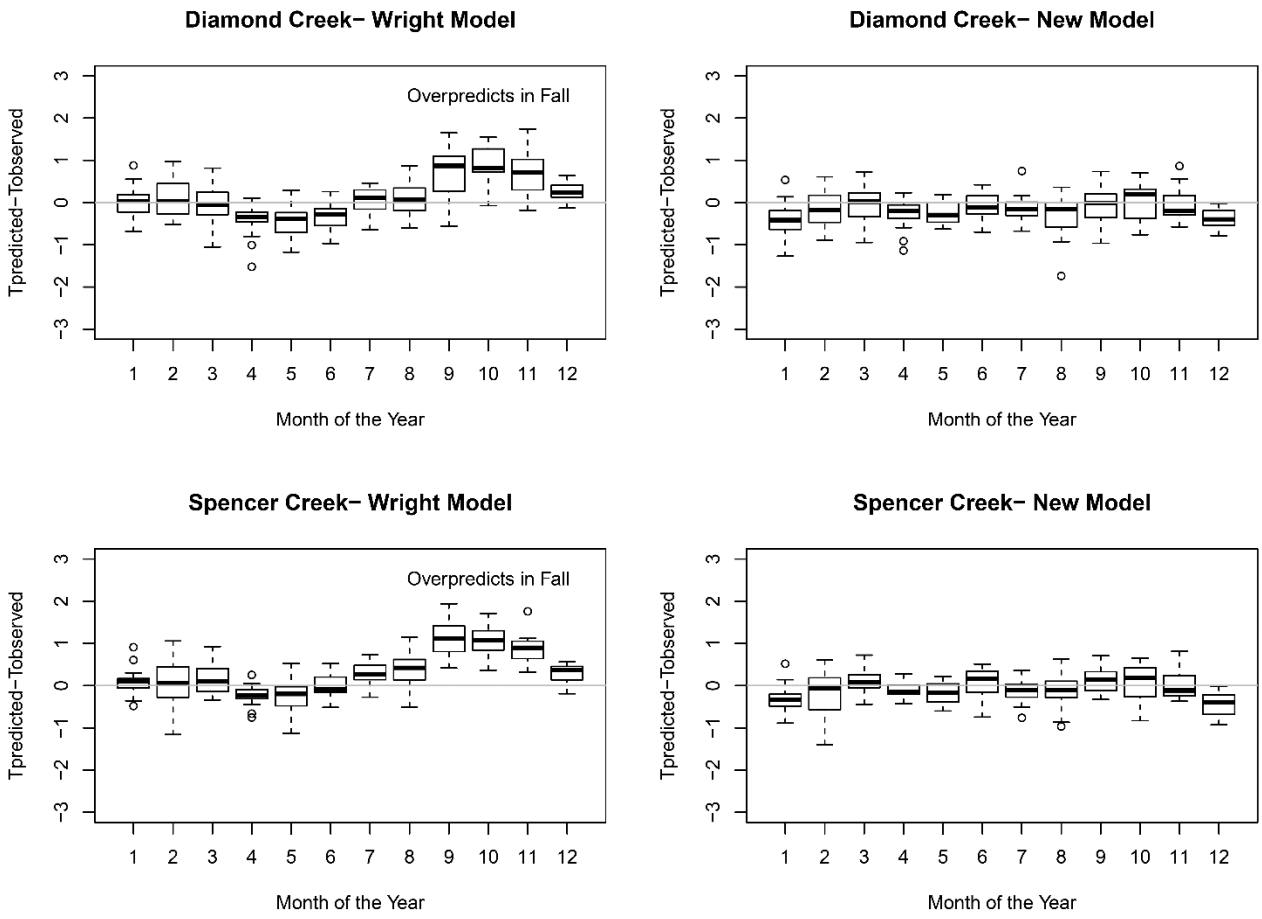


Figure 1. Comparison of residuals from the current model used for modeling water temperature in Grand Canyon (linear; Wright and others, 2009) relative to the new model we developed that includes an exponential decay in warming combined with the use of other data sources including solar radiation. The 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 (RM 224) and Spencer Creek (RM 244).

Development of a refined water temperature model for Grand Canyon combined with a plethora of water temperature and discharge data already collected as part of the tailwater synthesis project from other reaches in the CRe (FY 2013-14 Work Plan, Project Element H.4; FY 2015-17 Work Plan, Project Element 9.8) provided an opportunity to expand water temperature modeling to other river segments in the basin with minimal effort. The results have provided context in discussions of the current and potential future distribution of native, recovering fish populations, recreationally important coldwater trout species, and potential future invaders into Grand Canyon (e.g., smallmouth bass) from upstream and downstream sources (Figure 2). This could inform upcoming decisions about allocation of water supply among the basins' existing reservoirs as runoff declines and air temperatures warm.

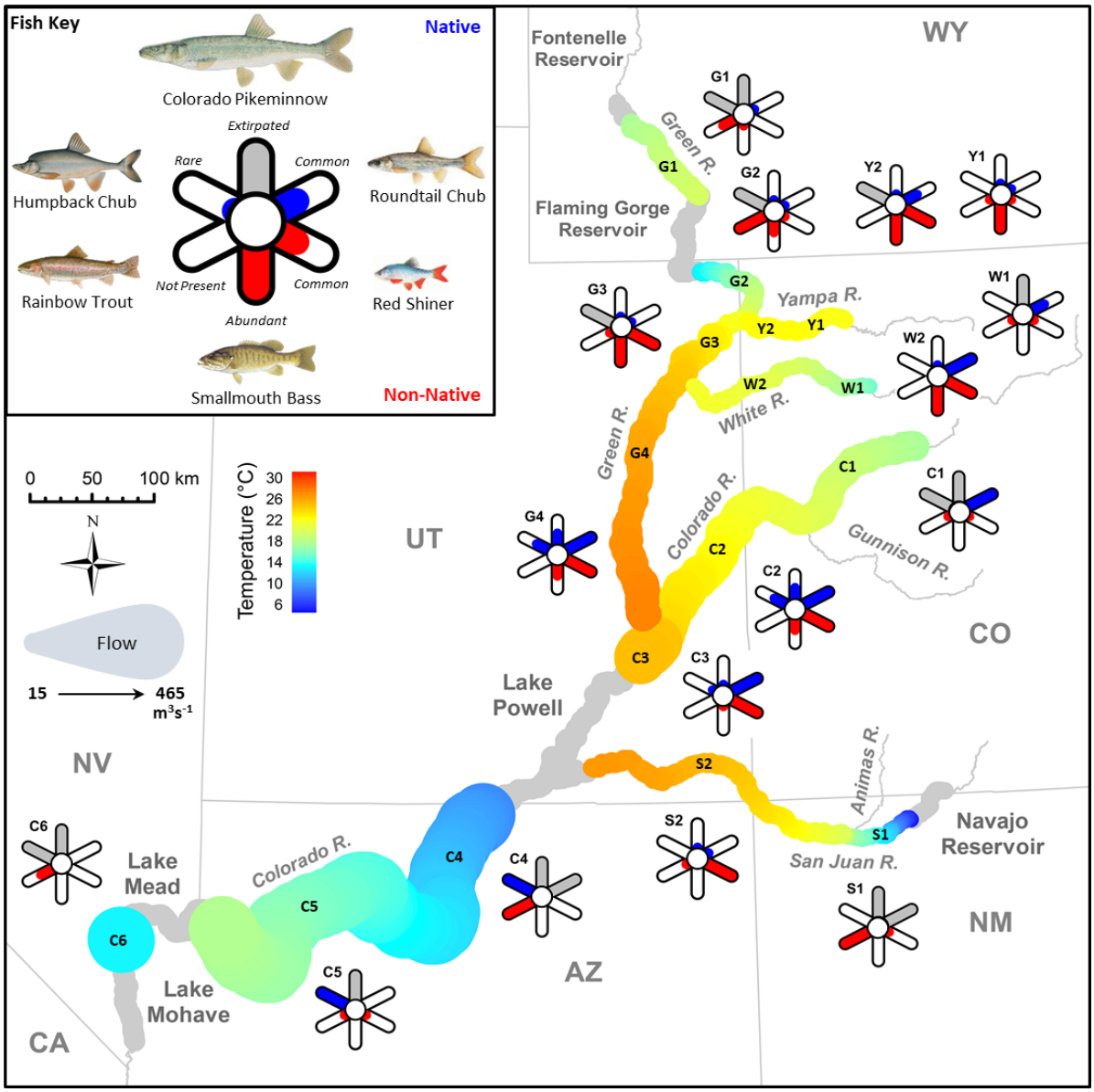


Figure 2. Heat map showing current water temperatures (6 – 26°C) in the CRe in Grand Canyon and in the upper and lower basin in July compared to the distribution and relative abundance of native, endemic fish populations (humpback chub, Colorado pikeminnow, roundtail chub), recreationally-important rainbow trout, and warmwater nonnatives (smallmouth bass, red shiner) that have hindered native fish recovery efforts in the upper basin. The Grand Canyon segment is currently much cooler than the upper basin river segments, which may be preventing the spread of undesirable warmwater nonnatives into Grand Canyon that could hinder recovery efforts for humpback chub.

Sub-element E.1.2.

The purpose of this project is to characterize spatial and temporal patterns in Colorado River nutrient availability downstream of 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 2019 we focused on the effects of two experimental flow regimes on phosphorus availability from the dam outflow, the role of storm-based inputs of phosphorus from the Paria River, and the potential for a wildfire to influence phosphorus pools in the CRe food web.

Because phosphorus concentrations in Lake Powell vary by depth, we hypothesized that the fall 2018 HFE and experimental bug flows implemented during the spring and summer of FY 2018 would affect downstream phosphorus concentrations. Sampling at the Lake Powell Wahweap station before, during, and after the High-Flow Experiment (HFE) in November 2018 revealed that SRP concentrations were approximately twice as high at the depth of the jet bypass tubes (4-7 ug/L) than at the depth of the penstocks (2-3 ug/L). A basic mixing model suggests that the discharge coming from the jet bypass tubes during the HFE should have elevated the outflow SRP concentration by about 1 ug/L (the detection limit of our analysis methods). Indeed, sampling at Lees Ferry before and during the HFE shows that SRP concentrations were higher during the HFE compared to before the HFE (Figure 3).

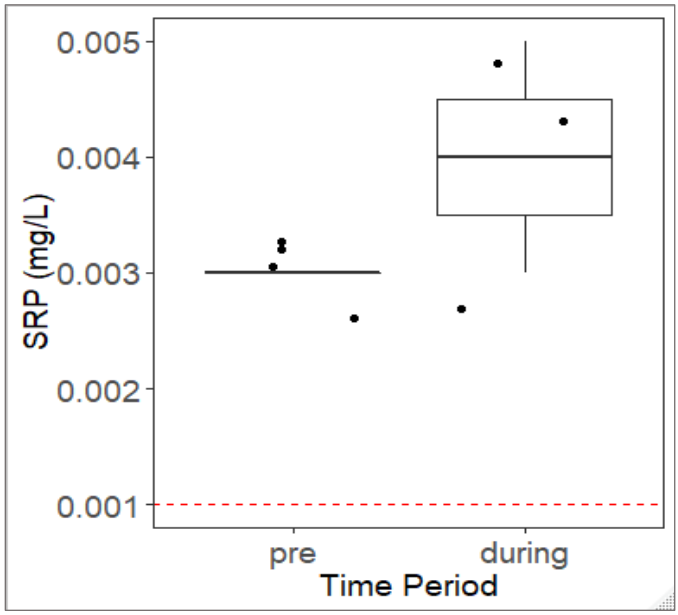


Figure 3. Soluble reactive phosphorus (SRP) concentrations (mg P L-1) at Lees Ferry prior to and during the 2018 HFE (n=4 for the "pre" time period and n=3 for the "during" time period). The red dashed line indicates the method detection limit for SRP. Individual data points are also shown.

Bug flow sampling during FY 2018 was standardized for time of day and revealed no differences in total phosphorus or total dissolved phosphorus (TDP) in river water collected from the Glen Canyon reach (concentrations were always below the detection limit of 0.008 mg/L). No significant difference was found in SRP concentrations; however, concentrations were more variable during weekend water (undetectable to 0.004 mg/L) than during weekday water (0.001-0.002 mg/L). To follow up on the higher variation in SRP during weekend water, we conducted nutrient sampling four times per day across two weekend water days and three weekdays in August of 2019. During this August sampling campaign there were no significant differences in SRP, TDP, or TP concentrations and very low variation in SRP between weekend and weekday water. Still, there was generally high variation in TP concentrations across the entire sampling period, ranging from 0.006-0.018 mg/L (n=14). We also observed significantly higher nitrate concentration (by about 0.04 mg/L NO3-N) during weekdays than on the weekend (two-sided t-test, p=0.01).

The Galahad fire occurred in the Shinumo watershed in May of 2014 and was followed by a large storm in August of 2014. Given the potential for fire to mobilize P and increase its rate of delivery to waterways (Emelko and others, 2016), we hypothesized that emergent aquatic insects collected near the mouth of Shinumo would have a higher P signature after the fire than before the fire. We also hypothesized that this effect would mostly be seen along the Colorado River downstream of Shinumo (whereas the upstream reach could be considered a control in a before and after control impact (BACI) analysis). Using historic light trap samples collected along the Colorado River (as described in Kennedy and others, 2016), we selected samples collected within 25 river miles up or downstream of Shinumo from June-September in 2013, 2014, and 2015 (n~150). From these samples, we selected those that contained specimens of the order *Diptera* (n=54), and at least 4 individual *Diptera* were handpicked from the sample under a microscope for chemical analysis. *Diptera* were selected given their capability of reflecting a sizeable stream signature following emergence (Muehlbauer and others, 2014) and given their general abundance in Colorado River light trap samples. A small subset of the samples with the highest abundance of *Diptera* were run at the Colorado Plateau Stable Isotope Laboratory of Northern Arizona for analysis of d15N, %N, d13C, and %C (n=10). The remainder of the samples were weighed on a scale with an accuracy of 1 ug and shipped to the High Sierra Water Lab for total phosphorus analysis using a standard sulfuric acid digestion followed by spectrophotometric analysis and subsequent conversion to mg P per mg *Diptera* (n=44). There were no significant differences in %N, %C, d15N, or d13C across treatment groups, although C:N was generally lower post fire.

We found significantly higher 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 (Figure 4). Still, there was no effect of reach location (by two-way ANOVA), such that samples collected upstream after the fire were similarly elevated in P as those collected downstream. Over the same time, SRP outflow from Glen Canyon Dam was declining such that dam outflow chemistry is unlikely to be driving the patterns we observed. Collectively these results suggest that a large fire may have elevated the P content of *Diptera* in the CRe, but the role of other confounding factors such as changing water temperatures and P inputs from the Paria or Little Colorado Rivers need to be ruled out for a more conclusive interpretation.

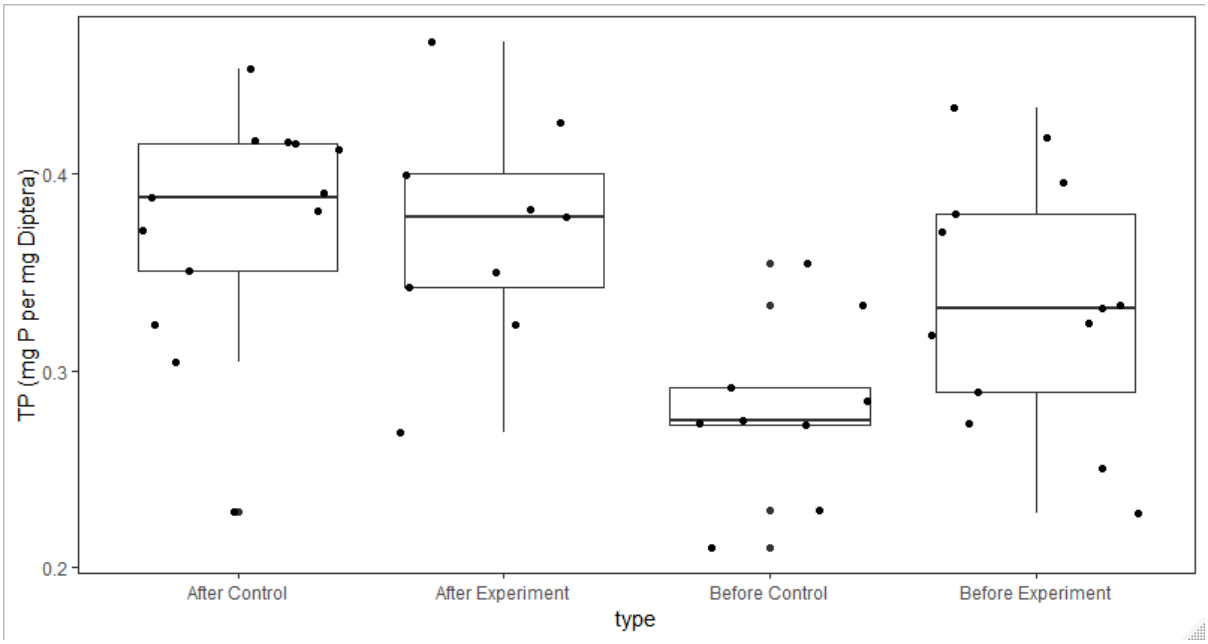


Figure 4. Total phosphorus content of *Diptera* specimens collected in light traps along the Colorado River before and after a major fire and subsequent storm in the Shinumo watershed. Samples collected within 25 river miles upstream of Shinumo were considered "control" whereas those collected within 25 river miles downstream were considered "experiment." There was significantly more phosphorus in *Diptera* after the fire than before (two-way t-test, $p<0.05$), but there was no reach effect.

While Glen Canyon Dam outflow dominates the water budget in the Colorado River, sampling conducted in FY 2018 suggests that the role of some larger tributaries may be important, at least during certain times of year in certain parts of the river, to the phosphorus budget. Storms, in particular, are often key times for phosphorus transport in river systems. The Paria River had the highest total phosphorus concentrations of any tributary tested during both FY 2017 sampling and a previous Arizona Department of Environmental Quality tributary

sampling effort (0.48 mg/L total P; Lawson, 2007). This combined with the relatively high discharges typical of the Paria River relative to other tributaries makes it a prime candidate for significant storm-driven phosphorus inputs to the Colorado River. Preliminary sampling during an August 2018 storm suggested that August storms alone could be responsible for 50% of the August total phosphorus loading and 8% of the annual loading. During FY 2019 a permit was obtained from NPS and a refrigerated ISCO automated water sampler was installed at the gage site where two other ISCOs are currently operated for sediment budgeting exercises. This ISCO is programmed for automated storm sample collection. A lack of monsoonal floods during FY 2019 precluded our ability to quantify storm-based phosphorus inputs from the Paria River, but we are well positioned to look at this question in FY 2020 as long as there are monsoonal (or winter) storms.

In addition, 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 phosphorus, bacteria and plants can also access other phosphorus fractions with varying levels of difficulty. Thus, it is important to characterize the quality (e.g., bioavailability) of phosphorus 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 phosphorus 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 phosphorus forms. The last-minute loss of a student intern resulted in the project's postponement until FY 2020.

Project Element 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. Preliminary analysis of 2018 data show a similar lack of seasonal synchrony. For example, significant declines in GPP were noted from summer to fall 2018 at some sites, but not others (Figure 5). In addition, our analyses have uncovered measurable differences in GPP from weekday to weekend water during bug flows, but with a response that differs depending on the location within the canyon. Finally, analysis of long-term data show declines in GPP following high flow events relative to years with no high flows (Figure 6). We plan to follow up on this finding with analysis of the 2019 dataset. In addition, we plan to use a combination of MiniDOT and long-term data to examine how GPP responds to other types of flow regulation such as HFEs, summer steady flows, and month-to-month changes in flow.

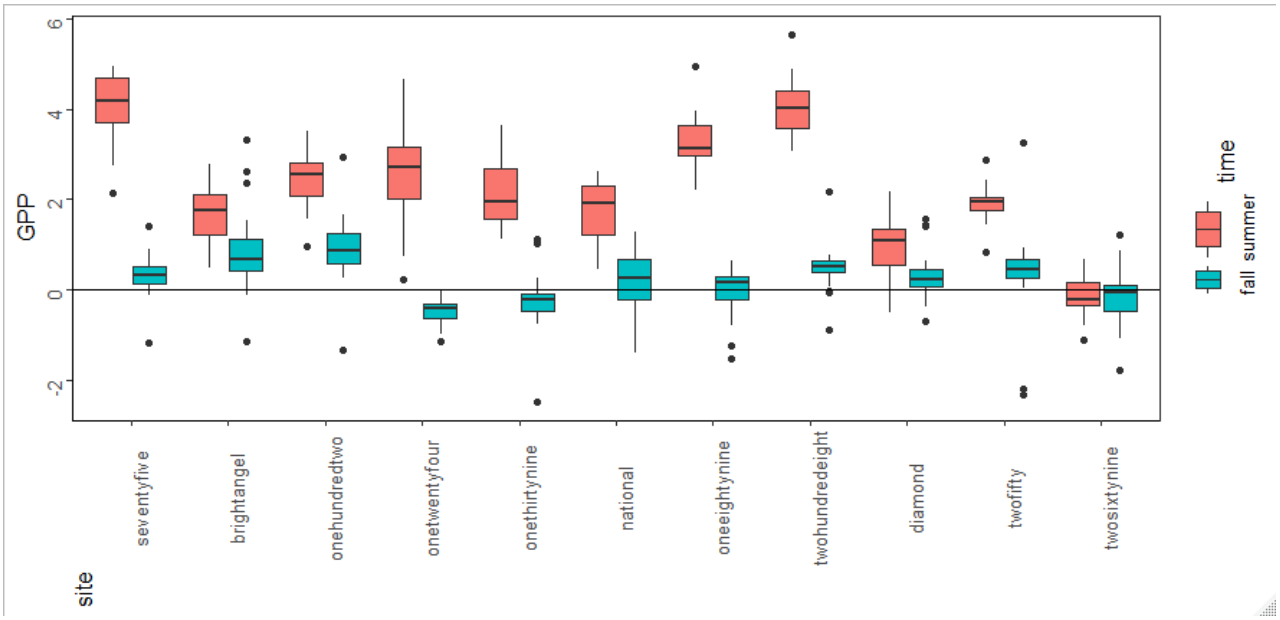


Figure 5. 2018 seasonal modeled GPP rates across at 11 sites with dissolved oxygen data in the Colorado River. GPP is in units of g O_2 m^{-2} d^{-1} and sites are ordered from the upstream-most site on the left to the downstream-most site on the right. Note that summertime GPP is much higher than fall gap at some sites (e.g. RMs 75, 124,189,208), but does not differ significantly seasonally at other sites (e.g. RM 269). "Summer" represents data collected between April 23 and May 10, 2018 (n=18 all sites) and "fall" represents August 30 through September 19, 2018 (n=21 all sites), where each data point is a single day GPP estimate.

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 river mile 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. Future work will employ this semi-mechanistic modeling approach at other sites along the river to better discern whole-ecosystem drivers.

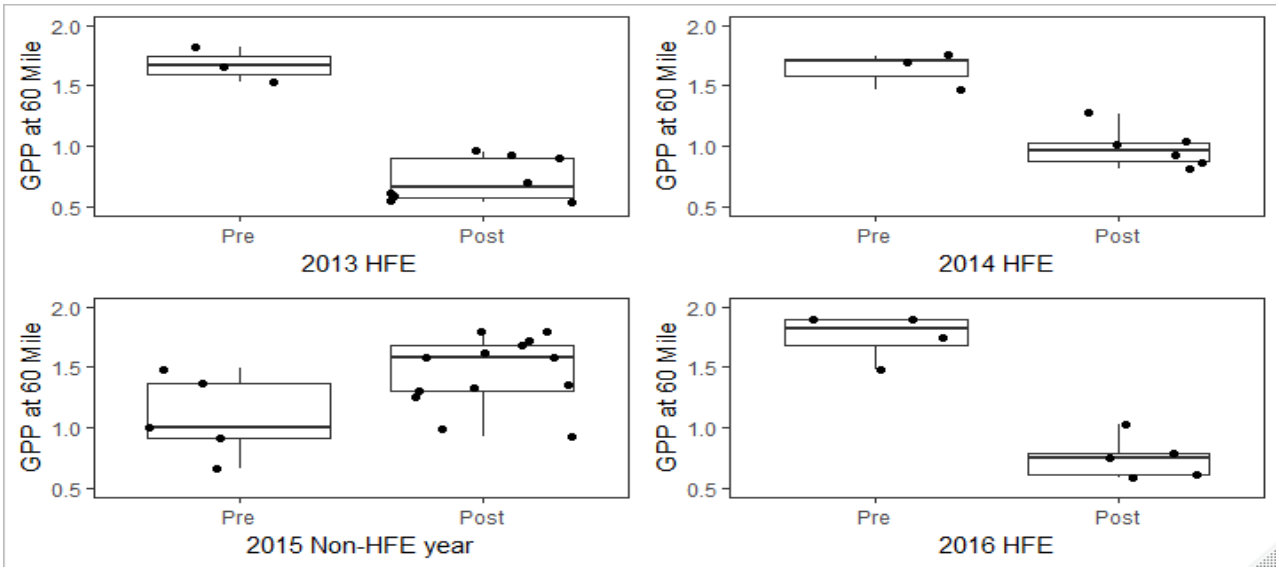


Figure 6. Modeled gross primary production (GPP) rates in the Colorado River at river mile 60 before "Pre," during "HFE," and after "Post" High-Flow Experiment (HFE) in 2013 (upper left), 2014 (upper right), and 2016 (lower right), as well as during a non HFE year where the approximate timing of fall HFEs was approximated (lower left). Each time period depicts approximately a week's worth of data with each point being a daily estimate of GPP. During years with HFEs, GPP declined significantly after the HFE. This stands in contrast to the non-HFE year where GPP did not decline markedly with time.

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 base of the food web as varying ecosystem drivers (nutrients, temperature) change in response to a decline in Lake Powell water levels from ongoing and anticipated future drought and warming air temperatures that further decrease flow into rivers and reservoirs in the southwest region.

In FY 2018 we completed the first step of this project by developing a program 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).

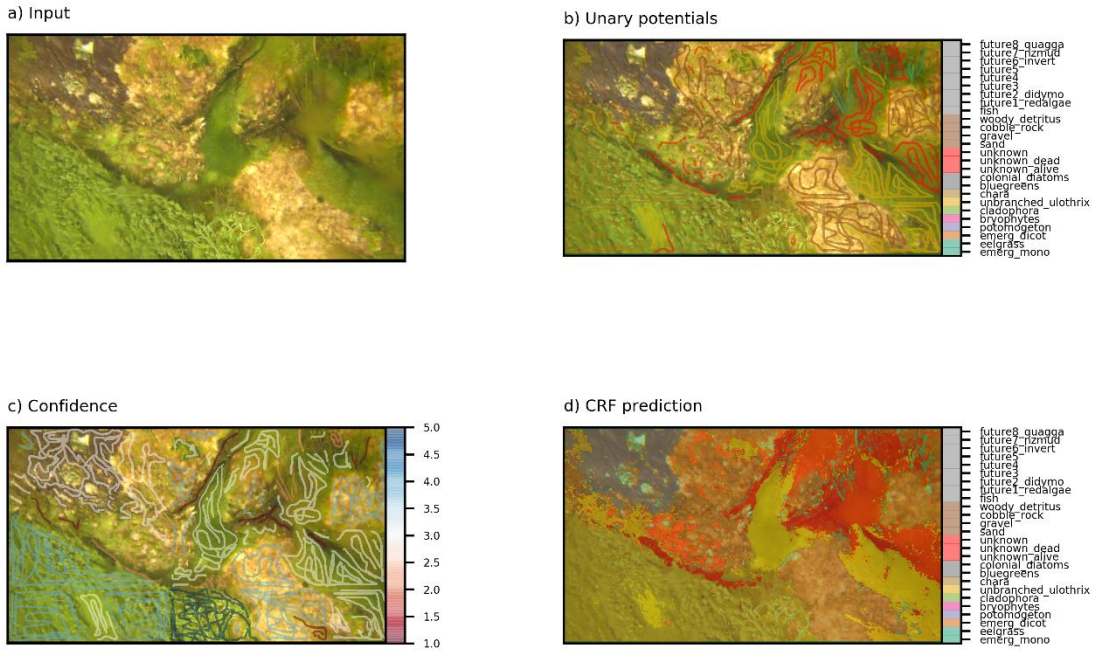


Figure 7. a) Underwater image taken in Lees Ferry (i.e., the input file); b) Manual on-screen image annotations that classify vegetation types at the pixel level (i.e., unary potentials); c) Confidence assigned to each unary potential by the manual annotator in "b"; and d) Predictions of vegetation cover 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, the PIs struggled to get the code to work within the cloud workspace. An alternative workflow was developed that will use of 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; model refinement will continue 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 took 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 meters apart. Analysis of those images is ongoing – it is anticipated we will have a fully functioning tool in FY 2020 based on underwater images taken in FY 2016, FY 2019, and an upcoming trip in FY 2020.

Sub-element E.2.3.

In FY 2018 we set up 12 replicate fiberglass raceways near the NPS Water Treatment Plant and Maintenance Shop in Lees Ferry for the purpose of using artificial stream experiments to study how aquatic vegetation, invertebrates, and fish may respond to elevated temperatures coming from potential future lower Lake Powell levels. While each recirculating tank was fed by water coming directly from the Colorado River through underground pipes ~200 meters away, the temperatures in our raceways 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 (TWP). 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.

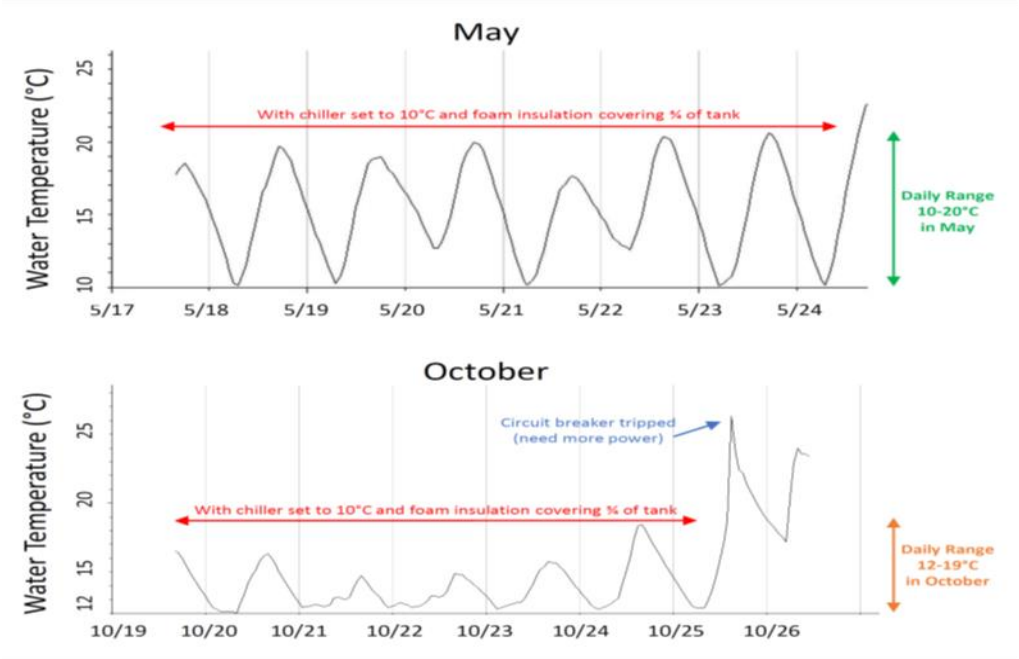


Figure 8. Temperature loggers were placed in tanks having a variety of temperature control mechanisms. These two plots represent the most extreme measures to control temperatures in the tanks, including placing a chiller in each recirculating tank with a foam insulation pad covering ¾ of the tank. Temperatures 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 developed a study design to answer research questions posed in the FY 2018-20 TWP, using all aspects of the CRe to simulate river conditions to the extent possible in a laboratory setting. For this study we posed the following questions: 1) how does GPP change in response to cold, cool, and warm 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 mud snails) 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, roundtail chub) consume mud snails? In June 2019 we collected cobble, algae, mud snails, and water from the Colorado River to inoculate 12 replicate raceways at the Rocky Mountain Research Station in Flagstaff. These raceways were located in an air temperature-controlled greenhouse to reduce variability in water temperatures. Each 150-gallon raceway was filled to approximately 100 gallons and a recirculating pump simulated flow within each tank; filters were removed to keep nutrient concentrations consistent. 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 (Figure 9).

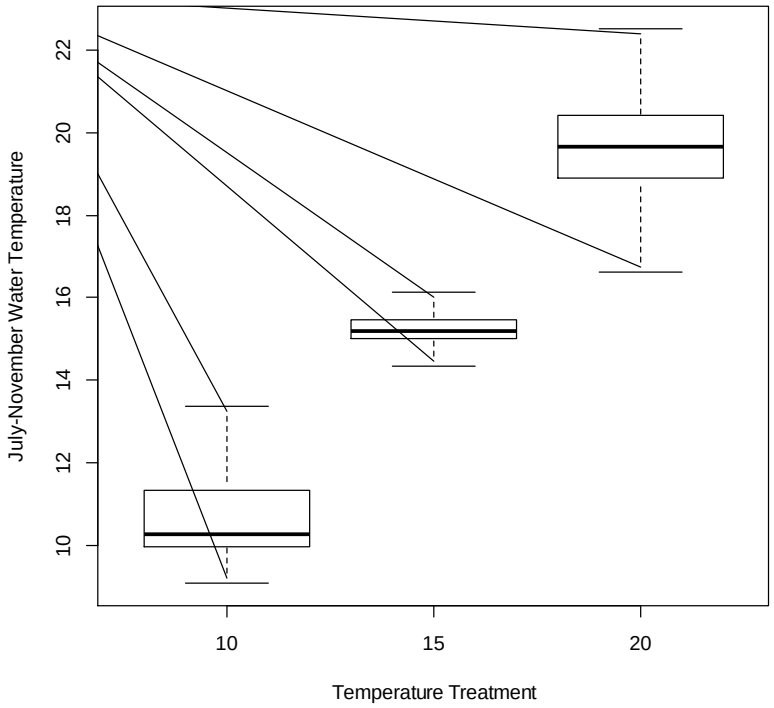


Figure 9. Boxplot of water temperatures in the four replicates for each temperature treatment (10, 15, and 20°C) in the artificial stream experiment. Water temperatures are logged every 1-hr; these data are from July 7 to November 7, 2019.

Artificial streams grew from June 21 to November 4, 2019 (Figure E.2.3c). To start the growing process, each tank was inoculated with 1 liter 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 mud snails 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. One tile was preserved in 3% Lugol's Solution on November 5, 2019 for analysis of diatom and soft-bodied algal communities. At the conclusion of the experiment (November 5-12) we conducted a whole-tank GPP experiment using the cobble from each basket to examine the effect of temperature treatments and grazing on GPP. A separate light experiment was conducted on November 12, 2019 to determine whether light levels varied by area of the greenhouse. Due to the recent end of this experiment, preliminary GPP, light, and mud snail data are not available—results will be forthcoming in FY 2020 to determine future research directions (Figure 10).

1) Experimental set-up in laboratory

2) Whole-tank GPP experiment

3) Mud snails in baskets

4) Algae growing on cobble after five months

Figure 10. Artificial stream experiment at the Rocky Mountain Research Station in Flagstaff. 1) Experimental setup with recirculating tank, baskets of cobble with mud snails (control, small, large snails), and gross primary production (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 mud snails; and 4) Algal growth after five months in artificial stream (June-November 2019).

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 currently in review in the journal *Limnology and Oceanography Letters*. This work was entirely funded outside of the GCDAMP. We are currently working to turn this conceptual model into a statistical model that links gross primary productivity, 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 and data management in the current workplan, which has required reducing staff and taking on additional outside projects to maintain staff that were only partially funded.

REFERENCES

Allen, A.P., Gillooly, J.F., and Brown, J.H., 2005, Linking the global carbon cycle to individual metabolism: Functional Ecology, v. 19, no. 2, p. 202-213, https://doi.org/10.1111/j.1365-2435.2005.00952.x.

Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., and West, G.B., 2004, Toward a metabolic theory of ecology: Ecology, v. 85, no. 7, p. 1771-1789, https://doi.org/10.1890/03-9000.

Chezar, H., and Rubin, D., 2004, Underwater microscope system—U.S. Patent no. US 6,680,795 B2: Washington, D.C., Secretary of the Interior, 9 p., https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/Chezar_2004.pdf.

Elser, J.J., Acharya, K., Kyle, M., Cotner, J.B., Makino, W., Markow, T.A., Watts, T., Hobbie, S.E., Fagan, W.F., Schade, J., Hood, J., and Sterner, R.W., 2003, Growth rate-stoichiometry couplings in diverse biota: Ecology Letters, v. 6, no. 10, p. 936-943, https://doi.org/10.1046/j.1461-0248.2003.00518.x.

Elser, J.J., Dobberfuhl, D.R., MacKay, N.A., and Schampel, J.H., 1996, Organism size, life history, and N:P stoichiometry: BioScience, v. 46, no. 9, p. 674-684, http://www.jstor.org/stable/1312897.

Emelko, M.B., Stone, M., Silins, U., Allin, D., Collins, A.L., Williams, C.H.S., Martens, A.M., and Bladon, K.D., 2016, Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems: Global Change Biology, v. 22, no. 3, p. 1168-1184, https://doi.org/10.1111/gcb.13073.

Hall, R.O., Jr., Yackulic, C.B., Kennedy, T.A., Yard, M.D., Rosi-Marshall, E.J., Voichick, N., and Behn, K., 2015, Turbidity, light, temperature, and hydropeaking control primary productivity in the Colorado River, Grand Canyon: Limnology and Oceanography, v. 60, no. 2, p. 512-526, https://doi.org/10.1002/lno.10031.

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

Lawson, L., ed., 2007, A water quality investigation of seventeen Grand Canyon tributaries—July 2004-May 2005: Phoenix, Arizona Department of Environmental Quality, Division of Water, Surface Water Section, publication no. OFR-07-04, 88 p., http://www.azdeq.gov/environ/water/assessment/download/gcreport.pdf.

Muehlbauer, J.D., Collins, S.F., Doyle, M.W., and Tockner, K., 2014, How wide is a stream? Spatial extent of the potential "stream signature" in terrestrial food webs using meta-analysis: Ecology, v. 95, no. 1, p. 44-55, https://doi.org/10.1890/12-1628.1.

Vernieu, W.S., 2009, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964-2013 (ver. 3.0, February 2015): U.S. Geological Survey Data Series 471, 23 p., https://doi.org/10.3133/ds471.

Walters, C., Korman, J., Stevens, L.E., and Gold, B., 2000, Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon: Conservation Ecology, v. 4, no. 2, article 1, http://www.consecol.org/vol4/iss2/art1/.

Wright, S.A., Anderson, C.R., and Voichick, N., 2008, A simplified water temperature model for the Colorado River below Glen Canyon Dam: River Research and Applications, v. 25, no. 6, p. 675-686, https://doi.org/10.1002/rra.1179.

Yvon-Durocher, G., Caffrey, J.M., Cescatti, A., Dossena, M., Giorgio, P.d., Gasol, J.M., Montoya, J.M., Pumpanen, J., Staehr, P.A., Trimmer, M., Woodward, G., and Allen, A.P., 2012, Reconciling the temperature dependence of respiration across timescales and ecosystem types: Nature, v. 487, no. 7408, p. 472-476, https://doi.org/10.1038/nature11205.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Presentation	Catchment and management characteristics are key in determining reservoir response to climate change	March 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—Invited talk: San Juan, Puerto Rico, Feb 24-March 1, 2019, Association for the Sciences of Limnology and Oceanography.
Presentation	Water storage decisions in response to drought in the Colorado River Basin will drive aquatic ecosystem dynamics	Oct 2019		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—Invited talk: Reno, Nev., Sept 29-Oct 3, 2019, 149th American Fisheries Society Annual Meeting and Joint Conference with the Wildlife Society.
Journal article	Water storage policy will determine future persistence, and biogeography of, imperiled river fishes in a changing climate		To be submitted Dec 2019	Dibble, K.L., Yackulic, C.B., Schmidt, J.C., Kennedy, T.A., and Bestgen, K.R., *in prep*, Water storage policy will determine future persistence, and biogeography of, imperiled river fishes in a changing climate: Frontiers in Ecology and the Environment.
Journal article	Dam management effects on gross primary production in a large regulated river		To be submitted Sept 2020	Deemer, B.R., Yackulic, C.B., Hall, R.O., Kennedy, T.A., J. Muehlbauer, J.D., Yard, M.D., *in prep*, Dam management effects on gross primary production in a large regulated river.

Project F: Aquatic Invertebrate Ecology

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

SUMMARY

Overview

The principal goal of our work this year was to track invertebrate population response to the second year of the Bug Flow experiment that was tested from May-August 2019. We designed the Bug Flows hydrograph in collaboration with Western Area Power Administration (WAPA) and Bureau of Reclamation staff. We monitored ecosystem response to the Bug Flow experiment by launching Grand Canyon river trips in April, May, and September, through continuation of long-term citizen science monitoring in Grand Canyon, continuation of monthly drift and insect emergence monitoring in Glen Canyon, and intensive invertebrate and fish sampling in Glen Canyon in June and August. 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.

Accomplishments

In FY 2019 our group worked with the Bureau of Reclamation and WAPA to design and implement the hydrograph for the Bug Flows experiment. 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.

To quantify the effects of Bug Flows, we launched three Grand Canyon river trips (April, May, and September). The objectives of the April and September trips were 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 was collected in 2017 and 2018. The purpose of the May river trip was to study food base response to the onset of the Bug Flow experiment. For the first weekend of Bug Flows in May, we

collected drift, sticky traps, light traps, and surveyed for insect eggs in the vicinity of the Little Colorado River confluence (~ river mile (RM) 61). For the second weekend of Bug Flows in May, we carried out this same sampling in the vicinity of Fall Canyon (~RM 211) where humpback chub populations have been increasing. Sample processing for all three FY 2019 river trips is ongoing.

Citizen science light trapping of adult aquatic insects has been ongoing since 2012, 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. For example, 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). Citizen science data also indicate the abundance of midges was significantly higher Canyon-wide during weekend Bug Flow releases compared to weekdays with load-following flows (Figure 2).

Citizen science sampling yielded 1,100 light trap samples in 2019. Although we do not anticipate completing sample processing until March 2020, most citizen science samples will be processed by January 2020 and these results will be included in our Annual Reporting Meeting presentation. Citizen scientists also collected acoustic bat activity data paired with over 400 of these light trap samples. These paired insect-bat 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.

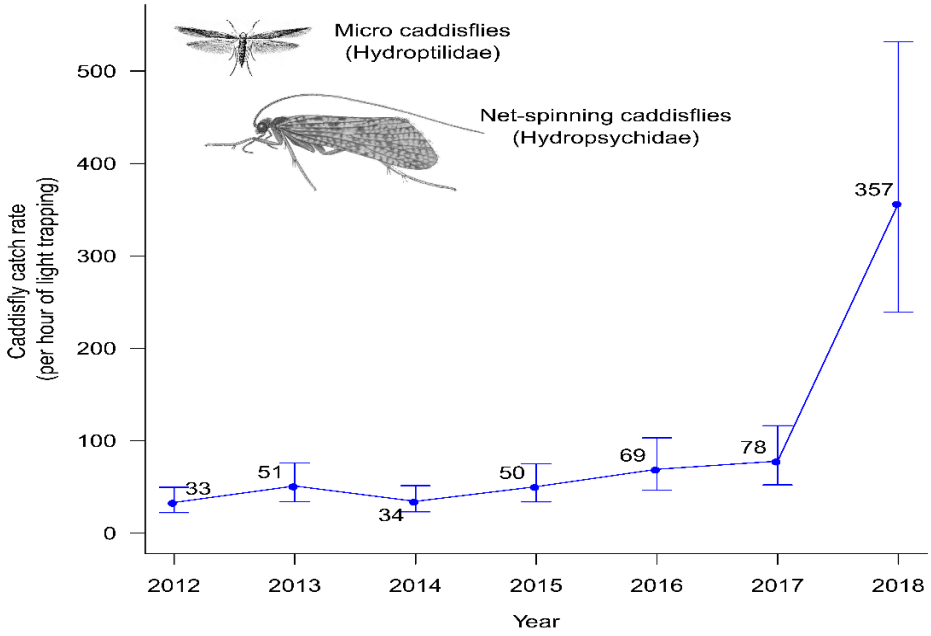


Figure 1. There was a significant increase in the number of adult caddisflies captured in citizen science light traps during the first year of Bug Flows in 2018 compared to 2012-2017 light trap samples. Bars represent standard error and numbers represent mean light trap catch rates. Caddisflies are in the Order Trichoptera, which is part of the sensitive "EPT" indicator group.

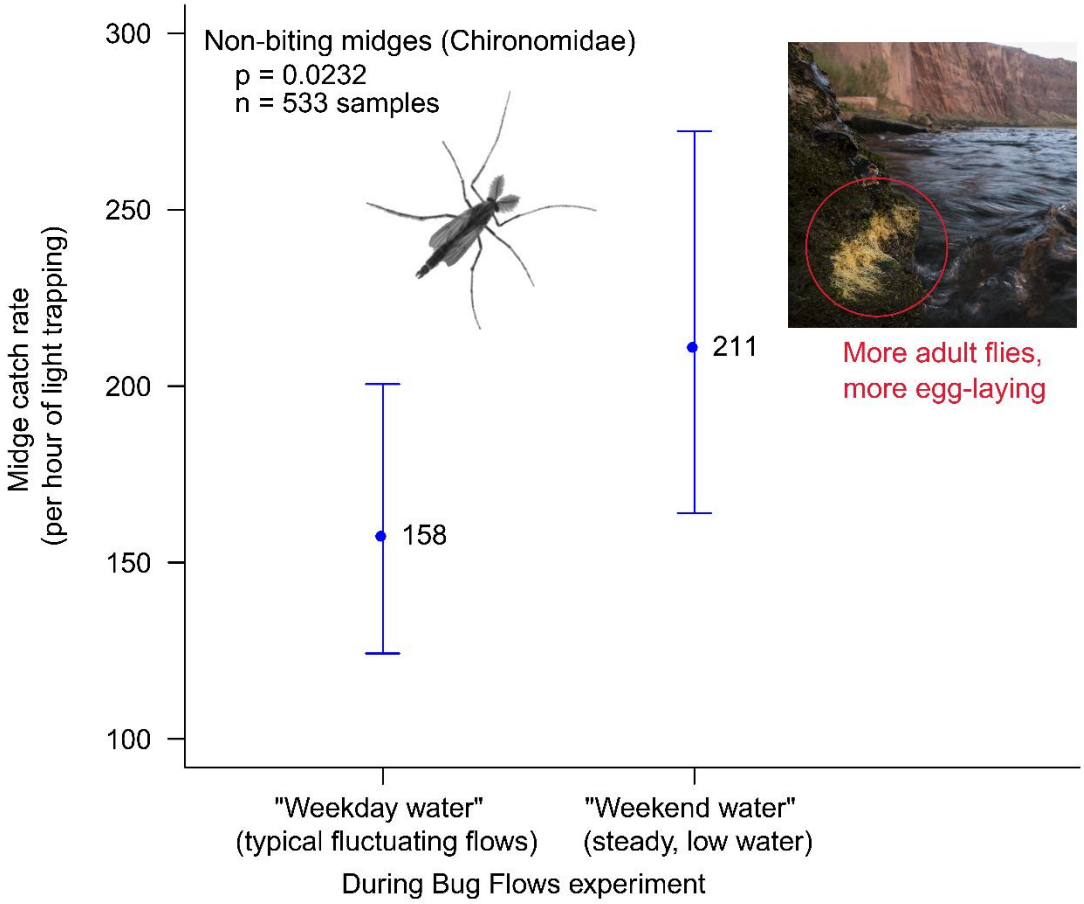


Figure 2. During Bug Flows in 2018, more adult non-biting midges (Chironomidae) emerged during low and steady Bug Flow weekend water conditions than during normal, fluctuating weekday water conditions. Bars represent standard error and numbers represent mean light trap catch rates throughout Grand Canyon. Inset photo shows hundreds of yellow "egg ropes" laid by midges at the air-water interface on a rock in Glen Canyon in August 2019. Each egg rope contains hundreds of midge eggs. Photo by David Herasimtschuk, Freshwaters Illustrated/USGS.

Our group continued long-term monitoring of the aquatic food base in the Lees Ferry sport fishery with 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 and up-to-date (i.e., there is no backlog). 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.

In response to concerns raised by WAPA, we conducted intensive sampling in Glen Canyon to determine the short-term response of invertebrate drift, insect emergence, rainbow trout feeding habits, and angling success to the Bug Flows experiment. Sampling occurred from June

14-17 and August 23-26, Friday-Monday in both cases. Each sampling event included two days with load-following flows and two weekend days with low steady discharges for Bug Flows. On each day, invertebrate drift samples were collected at five sites (RM -15, -12.9, -8, -3.5, and 0) and starting at two different times of day (6 am, 3 pm; sampling took around 2 hours to complete). On weekdays during load-following, the two sample times correspond to low and high (on-peak) discharge while during weekend Bug Flows the two sample times correspond to identical, low discharges. Rainbow trout diet samples were collected daily using non-lethal gastric lavage from trout collected by guided angling. Volunteer anglers helped capture rainbow trout used in this diet study. Invertebrate and fish diet sample processing from this experiment is ongoing. However, results from the angling success portion of the study have been analyzed and demonstrate that the average angler caught more fish during low steady Bug Flows compared to load-following flows (Figure 3). This finding is consistent with numerous fishing blogs from Lees Ferry guide services describing how low steady Bug Flow releases improves angling success.

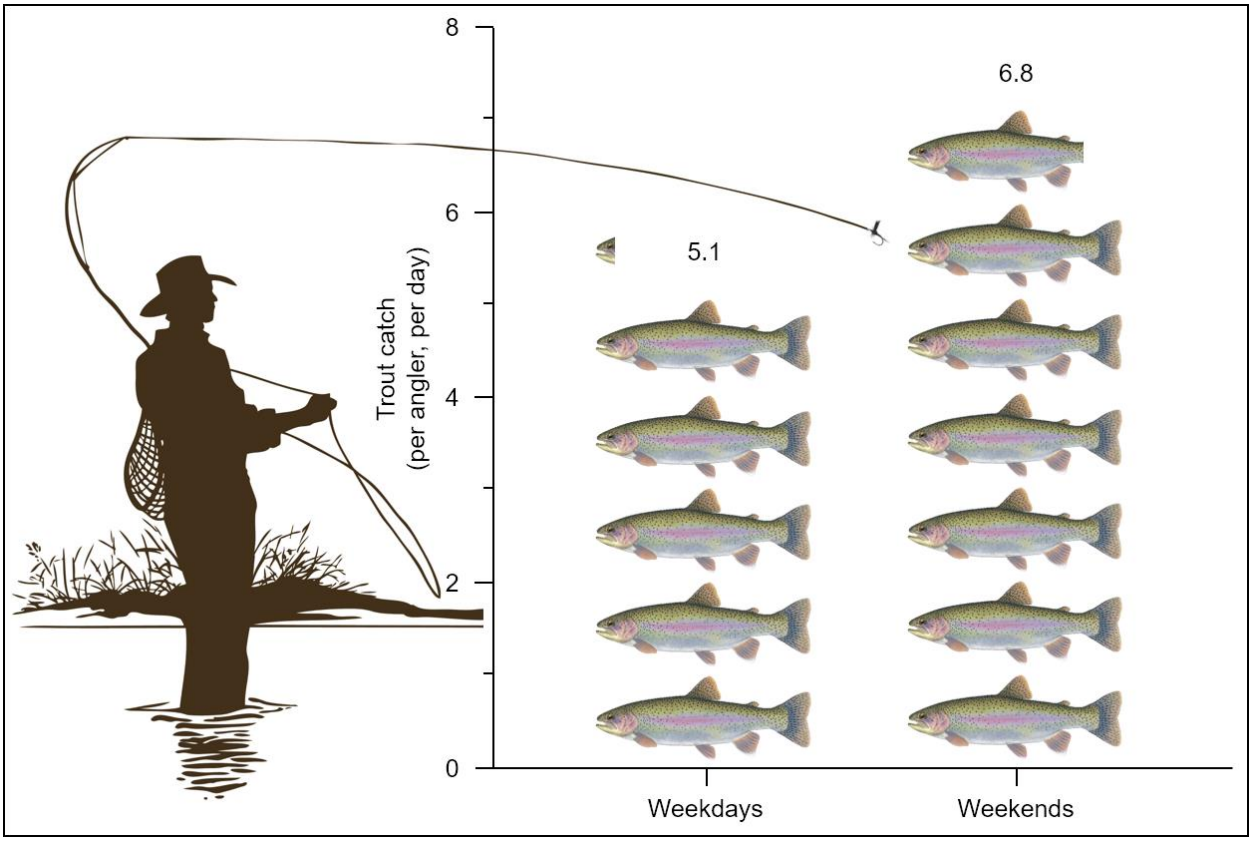


Figure 3. Modeled number of fish captured by anglers during weekday load-following flows compared to low steady Bug Flow weekends. In our study involving 31 anglers, we caught 368 fish over 8 days (4 weekdays and 4 weekend days). On average, 5.1 fish were caught per angler on the weekdays compared to 6.8 fish caught per angler on weekend days (+/- standard error of 0.62 and 1.02, respectively).

In response to manager concerns, our group continued studies of the food base in Bright Angel Creek associated with trout mechanical removal efforts and 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 three times in FY 2019 (November 2018 and June and September 2019; a planned January trip was canceled due to the government shutdown). In total, we collected 36 benthic, 27 drift, and 36 sticky trap samples of aquatic insects in the 3200-m reach upstream from the mouth of Bright Angel Creek. We have been conducting these 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.

Next Steps

Our results suggest that Bug Flows had a strong, positive impact on the aquatic food base in Glen, Marble, and Grand Canyons. Our data also demonstrate that weekend low steady Bug Flow releases improve angler catch rates in the rainbow trout sport fishery compared to weekday load-following flows.

In FY 2020, we will continue our long-term monitoring of drift and sticky trap collections in the Glen Canyon reach, our citizen science light trap sample collection throughout Glen, Marble, and Grand Canyons, our drift-focused river trips in spring and fall, and our drift sampling on juvenile chub monitoring and rainbow trout monitoring trips (see projects G and H). Collectively, these data collections provide important insight into the long-term status and trends of the aquatic food base in the Colorado River ecosystem, particularly as it pertains to food resources for rainbow trout and humpback chub. These data collection efforts also allow us to track food base response to Bug Flow experimentation on robust spatial and temporal scales. Finally, contingent on funding and testing the Bug Flow experiment again in 2020, we will also repeat the intensive weekday-weekend study in Glen Canyon to more fully characterize how Bug Flows affect aquatic resources and angling success on a daily scale.

REFERENCES

Whiting, D.P., Paukert, C.P., Healy, B.D., and Spurgeon, J.J., 2014, Macroinvertebrate prey availability and food web dynamics of nonnative trout in a Colorado River tributary, Grand Canyon: Freshwater Science, v. 33, no. 3, p. 872-884, https://doi.org/10.1086/676915.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Series, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Bug Flows implementation and resource response	March 2019	Kennedy, T.A. and Muehlbauer, J.D., 2019, Bug Flows implementation and resource response—presentation: Phoenix, Ariz., March 12, 2019, TWG Annual Reporting Meeting.
Presentation	Big flood, small flood, spring flood, fall flood: HFE timing affects food base response	March 2019	Kennedy, T.A. and Muehlbauer, J.D., 2019, Big flood, small flood, spring flood, fall flood—HFE timing affects food base response—presentation: Phoenix, Ariz., March 13, 2019, TWG HFE workshop meeting.
Presentation	Bug Flows implementation and resource response	April 2019	Kennedy, T.A., 2019, Bug Flows implementation and resource response—presentation: Marble Canyon, Ariz., April 15, 2019, Meeting with fishing guides.
Presentation	Bug Flows evaluation and recommendation for 2019	April 2019	Smith, E.O., Kennedy, T.A., and Vanderkooi, S.P., 2019, Bug Flows evaluation and recommendation for 2019—presentation: Flagstaff, Ariz., April 22, 2019, LTEMP Planning and Implementation Team Webinar.
Presentation	Bug Flows update	May 2019	Kennedy, T.A., Muehlbauer, J.D., and Dodrill, M.J., 2019, Bug Flows update—presentation: Flagstaff, Ariz., May 1, 2019, TWG Webinar.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Series, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	When flow food webs get fishy: Some challenges and opportunities	May 2019	Baxter, C.V., Bellmore, J., Cross, W.F., Hall, R.O., Kennedy, T.A., Marcarelli, A., Paris, J., Rosi, E.J., 2019, When flow food webs get fishy—Some challenges and opportunities—presentation: Salt Lake City, Utah, May 20, 2019, Society for Freshwater Science Annual Meeting.
Presentation	Genetic diversity of a vagile aquatic insect varies with river network structure	May 2019	Metcalfe, A.N., Kennedy, T.A., Marks, J.C., Muehlbauer, J.D., 2019, Genetic diversity of a vagile aquatic insect varies with river network structure—presentation: Salt Lake City, Utah, May 20, 2019, Society for Freshwater Science Annual Meeting.
Presentation	Food web controls on mercury flux and fate in the Colorado River, Grand Canyon	May 2019	Walters, D., Rosi, E.J., Cross, W.F., Kennedy, T.A., Baxter, C.V., and Hall, R.O., 2019, Food web controls on mercury flux and fate in the Colorado River, Grand Canyon—presentation: Salt Lake City, Utah, May 20, 2019, Society for Freshwater Science Annual Meeting.
Presentation	Hydropower and aquatic-terrestrial linkages in the Colorado River	May 2019	Lupoli, C.A., Kennedy, T.A., Sabo, J.L., and Yackulic, C.B., 2019, Hydropower and aquatic-terrestrial linkages in the Colorado River—presentation: Salt Lake City, Utah, May 21, 2019, Society for Freshwater Science Annual Meeting.
Presentation	Bug Flows: LTEMP planning process and preliminary observations	May 2019	Smith, E.O. and Kennedy, T.A., 2019, Bug Flows—LTEMP planning process and preliminary observations—presentation: Flagstaff, Ariz., May 22, 2019, AMWG Webinar.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Series, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Colorado River ecosystem response to the 2018 Bug Flow experiment from Glen Canyon Dam	May 2019	Muehlbauer, J.D. and Kennedy, T.A., 2019, Colorado River ecosystem response to the 2018 Bug Flow experiment from Glen Canyon Dam—presentation: Salt Lake City, Utah, May 23, 2019, Society for Freshwater Science Annual Meeting.
Presentation	Preliminary observations from the Bug Flows Experiment	June 2019	Kennedy, T.A. and Muehlbauer, J.D., 2019, Preliminary observations from the Bug Flows Experiment—presentation: Phoenix, Ariz., June 11, 2019, TWG Meeting.
Presentation	Colorado River Ecosystem response to the 2018 Bug Flow Experiment from Glen Canyon Dam	September 2019	Kennedy, T.A., Muehlbauer, J.D., and Rogowski, D.L., 2019, Colorado River ecosystem response to the 2018 Bug Flow Experiment from Glen Canyon Dam—presentation: Flagstaff, Ariz., September 11, 2019, 15th Biennial Conference of Research on the Colorado Plateau.
Presentation	Gene flow among net-spinning caddisfly populations in the Colorado River Basin	September 2019	Metcalfe, A.N., Kennedy, T.A., Marks, J.C., and Muehlbauer, J.D., 2019, Gene flow among net-spinning caddisfly populations in the Colorado River Basin—presentation: Flagstaff, Ariz., September 11, 2019, 15th Biennial Conference of Research on the Colorado Plateau.

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
Email	cyackulic@usgs.gov		
Telephone	(928) 556-7379		

SUMMARY

In 2019, humpback chub (HBC) research included sampling trips to the lower Little Colorado River (LCR), in the neighboring reaches of the Colorado River (near the LCR confluence), and in the Colorado River near Fall Canyon (in western Grand Canyon). The above-mentioned sampling efforts visited the same reaches across trips, and thus mark-recapture efforts were relatively intensive. To complement the more spatially-intensive sampling efforts, 2019 sampling also included more widespread sampling of the Colorado River via HBC aggregations and backwater seining trips. These sampling trips visited many sites along the Colorado River and sampling efforts were more diffuse along a larger spatial area. All monitoring efforts generally followed the same fish sampling protocol as described in Persons and others (2015).

Monitoring of the LCR in 2019 included U.S. Fish and Wildlife Service (USFWS)-led sampling in the lower 13.6 km of the LCR (two fall trips and two spring trips), which yielded abundance estimates from closed models. Furthermore, the USFWS also visited a more upstream site (located 13.6-17.7 river kilometers upstream of the Colorado River confluence) in May to conduct HBC monitoring and in October to translocate HBC juveniles from the lower LCR into upstream reaches. One additional trip to the lower 13.6 km of the LCR was conducted by USGS in June-July 2019, where the goal was to sample the age-0 cohort that was produced in the spring of 2019. Colorado River monitoring by the USGS in 2019 included May, July, and October sampling trips near the LCR confluence in the juvenile chub monitoring reach (located 62.8-65.9 river miles (RM) downstream of Lees Ferry - hereafter referred to as JCM-east). Similarly, May, July, and October 2019 trips also visited a site in western Grand Canyon (RM 210.5-214.0) referred to as the Fall Canyon reach or JCM-west.

Data from LCR monitoring and from JCM-east will be used to obtain estimates of vital rates (survival, growth) and adult HBC abundances from multistate models. Additionally, we are working on modeling methods to help us explore how to best integrate data from passive integrated transponder (PIT) tag antennas into humpback chub population models. Initial results of this effort suggest that PIT tag antennas are a powerful tool that can augment detections of larger adult fish (which tend to have low capture probabilities in hoop nets and with electrofishing). We are also developing models that explicitly incorporate information about alternative life histories and demographic groups (e.g., males versus females, small versus large adults), where survival and movement rates differ among these groups.

Project Element G.1. Humpback Chub Population Modeling

Progress on HBC population modeling includes initial development of a mark-recapture model of spawning dynamics in the LCR aggregation, construction of a model assessing the effectiveness of HBC translocations upstream of Chute Falls, and a recent manuscript submission that describes a new approach to model building that includes a modeling example from the LCR HBC aggregation.

The spawning dynamics model is being developed by USGS-GCMRC staff and researchers from Colorado State University. This model is designed to assess variability in survival, growth, and movement rates for different demographic groups (i.e., small females, large females, small males, large males) and alternate life history states (i.e., annual spawners, skipped spawners, residents). One important aspect of this model is that it explicitly incorporates antenna detections and physical capture data (e.g., hoopnet and electrofishing captures) into a mark-recapture model structure. Antenna data include both data from the LCR multiplexer array (MUX) that is located near the LCR-Colorado River confluence, as well as submersible antennas placed in the JCM-east reach. Initial results suggest that antennas detect trap-shy individuals that have not been captured in many years. For example, inclusion of LCR MUX data show that many adult HBC that swim into the LCR are not captured by USFWS as part of their spring sampling. This can be seen in the results of previous studies, which over-estimated skipped spawning probabilities (or the probability an adult in the Colorado River (CR) does not move into the LCR to spawn in spring) either because the models did not include antenna data (Yackulic and others, 2014) or because the models included antenna data that were of poor quality (Pearson and others, 2015). Comparison of models fit with and without antenna data also show that models without antenna data also tend to underestimate survival of large adult spawners (Figure 1).

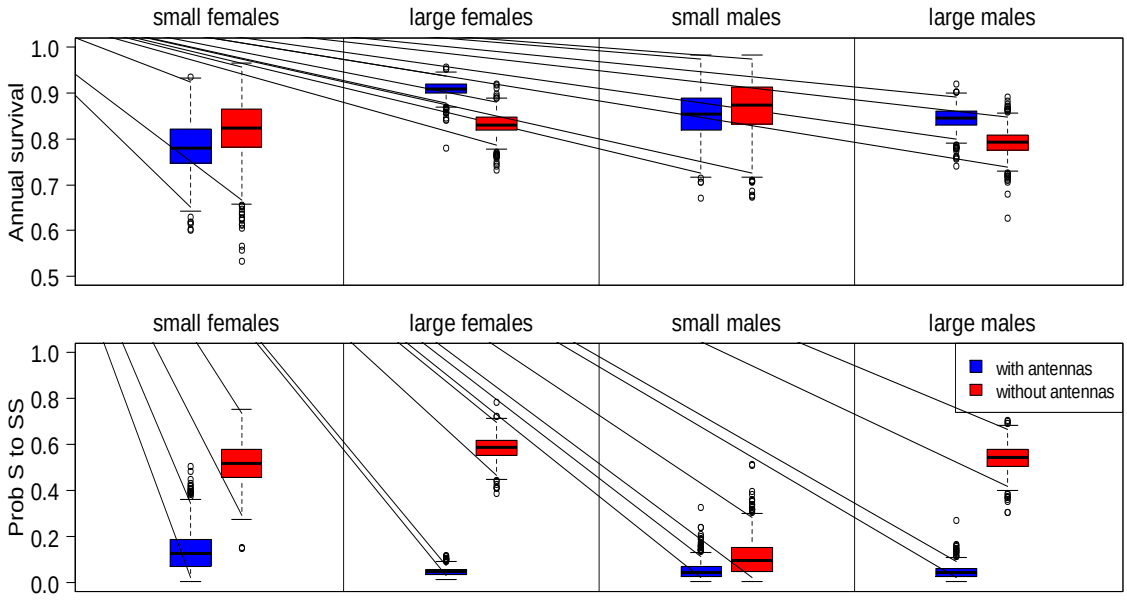


Figure 1. Comparison of two models fit with and without antenna data. Data were fit from 2009-2017 and include different biological states which include spawner (moves between Colorado and Little Colorado Rivers in spring), skipped spawner (in Colorado River year-round), and resident (in Little Colorado River year-round). The top panel shows the mean annual survival probability for the spawners for four demographic groups: small females (200-249mm TL), small males (200-249mm TL), large females (250+mm TL), and large males (250+mm TL). The lower panel shows the mean probability that a annual spawner becomes a skipped spawner according to demographic group. Graphs indicate that models fit without antenna data may over-estimate the probability of annual spawners becoming skipped spawners and underestimate survival of large adult spawners.

Additionally, USGS and USFWS are collaborating to construct a model that estimates the effectiveness of USFWS translocations above Chute Falls. Results suggest that the translocations produce a modest increase in the size of the LCR adult HBC population. Specifically, the continuous effort of translocating 300 juvenile HBC each year upstream of Chute Falls would be expected to result in an extra 350-400 adult HBC under equilibrium conditions, compared to no translocations. Importantly, these extra adult HBC should decrease the likelihood that other management actions, like trout removal, are required and we are working to estimate the size of this impact using a decision model.

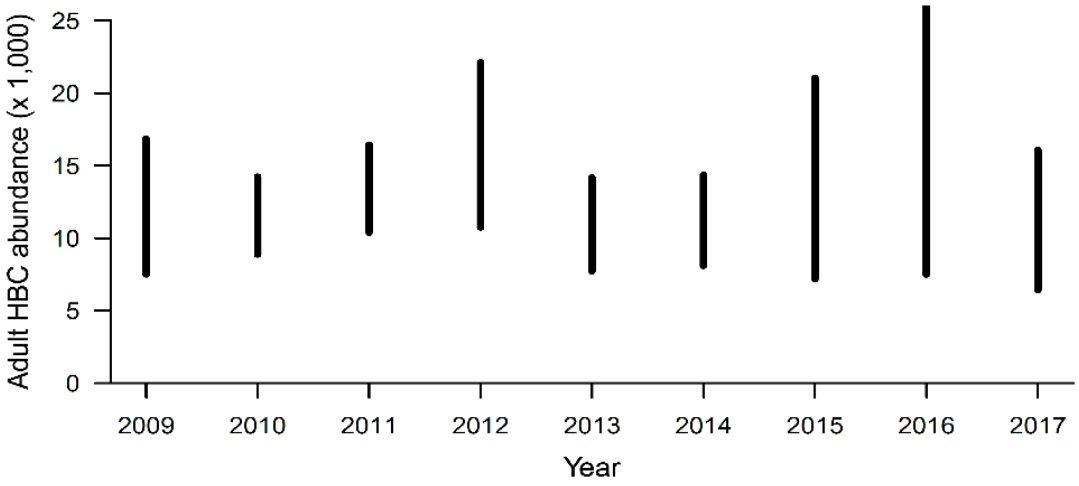


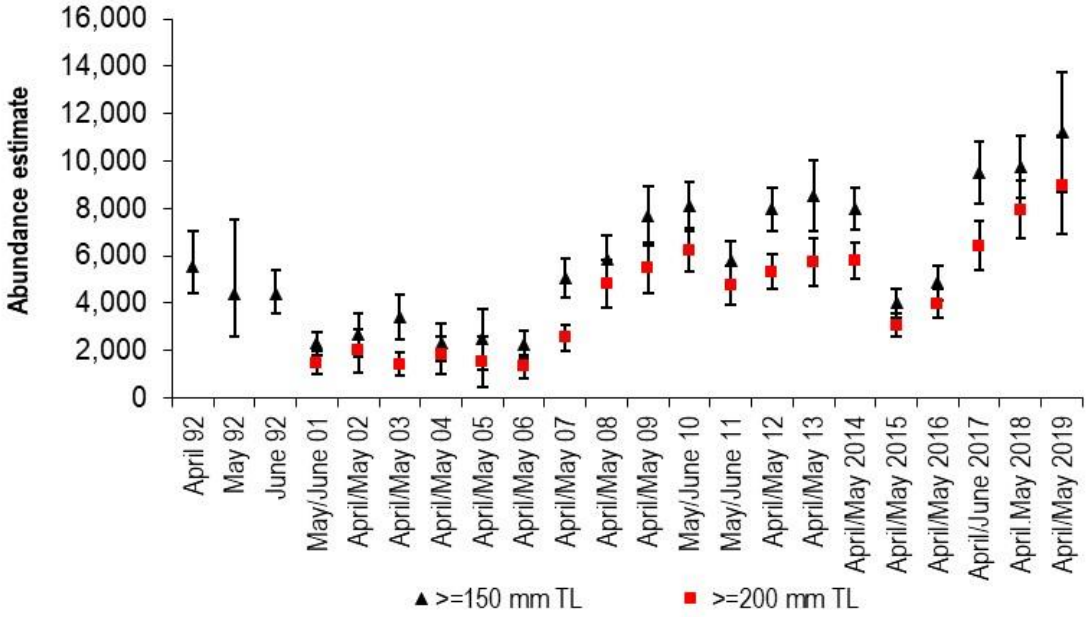
Figure 2. Abundance of adult humpback chub (HBC; >199mm TL) that spawn in the Little Colorado River. This figure is from a manuscript that was recently submitted to the journal Ecological Applications.

Lastly, the latest HBC population numbers are included in a manuscript (Figure 2; Yackulic and others, in review) that is currently in review in the journal Ecological Applications. This manuscript describes an approach to population modeling that allows researchers to build faster and more complex mark-recapture models, and we are currently using the approach described in this paper to obtain better population models for HBC.

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

In 2019, USFWS and volunteers conducted four monitoring trips to monitor HBC in the LCR. These trips occurred in April, May, September, and October. The goal of these trips was to monitor the population status and trend of HBC in the LCR during spring and fall. During spring 2019, it was 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.

A.



B.

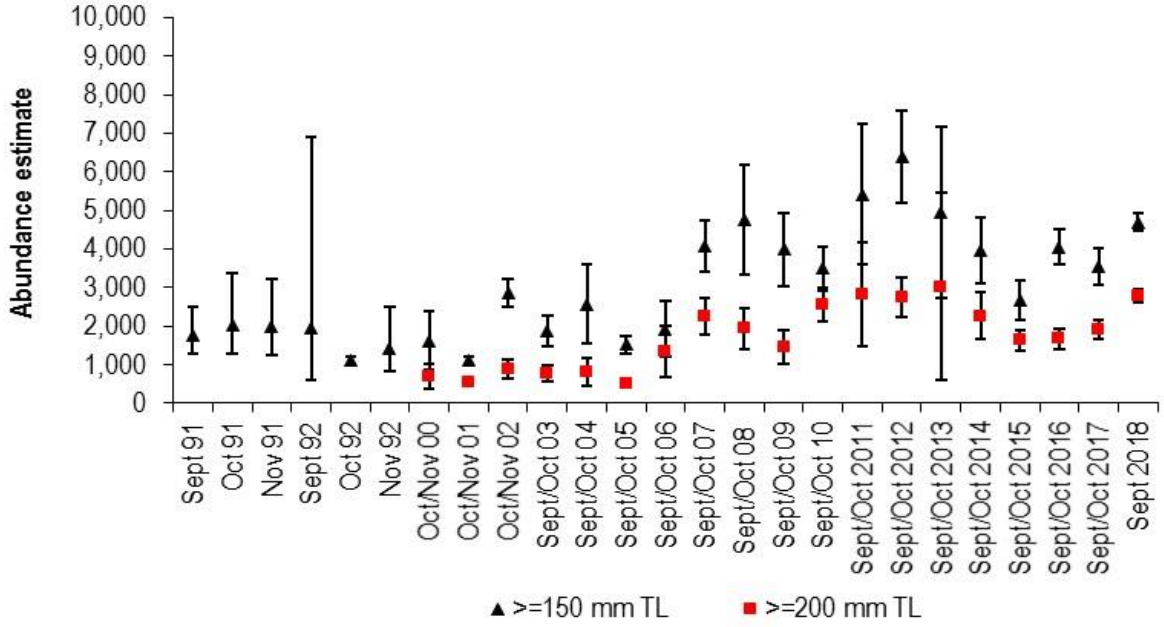


Figure 3. Chapman Petersen abundance estimates (±95% CI) of humpback chub ≥150 mm total length (TL) and ≥200 mm TL in the Little Colorado River (0-13.57 river km) during (A) spring (2001-2018) and (B) fall seasons (2000-2018). Note: closed spring and fall abundance estimates of humpback chub >150 mm TL in the Little Colorado River during 1991 and 1992 are from Douglas and Marsh (1996).

Fall 2019 abundance estimates are forthcoming. However, in fall 2018, it was estimated that there were 4,694 (SE=116) HBC ≥150 mm TL in the LCR. Of these fish, an estimated 2,779 (SE = 84) were ≥200 mm TL (Figure 3B). We add the caveat that the fall 2018 estimate was calculated by applying historical capture probability data to the September 2018 catch data, and that because of high variance in daily turbidity values during the September 2018 trip, this estimate may be conservative.

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

In 2019, there were three juvenile HBC monitoring trips (occurring in May, 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. All HBC > 79 mm TL were marked with PIT tags, and all HBC between 40-79 mm TL were marked using visual implant elastomer (VIE). One change that occurred during the July and October trips was that total length was only measured for recaptured fish.

Humpback chub were the most frequently caught species in JCM-east catch (1369), followed by flannelmouth sucker (1306), fathead minnow (784), rainbow trout (748), bluehead sucker (541), speckled dace (113), plains killifish (42), yellow bullhead (38), carp (26), brown trout (9), red shiner (9), channel catfish (8), and green sunfish (3). In total, all JCM-east trips captured 1038 HBC > 79mm TL and marked 275 HBC between (40-79 mm TL) with VIE. Catch of HBC >79mm TL was 143 in May, 246 in July, and 649 in October. In addition, the number of humpback chub given a VIE mark (between 40-79mm TL) was 35 in April, 51 in July, and 189 in October.

Table 1 compares PIT antenna data to the other two more conventional sampling types (electrofishing and hoop netting). Specifically, in the JCM-east reach, the PIT antennas detected more fish than what were captured using electrofishing and hoopnetting (1728 compared to 1147). Importantly, only 8.7% of fish in the JCM-east reach that were detected on antennas were also captured using hoop nets or electrofishing, showing there was low overlap in antenna detections and physical recaptures.

Table 1. Comparison of passive integrated transponder antennas (or fish scanners = FS) and physical capture methods (EF= electrofishing, HP= hoop net) for JCM-east and JCM-west reaches during 2019 sampling.

Description	Ivb Reach	Fall Cyn
Total Unique Tags Detected by Fish Scanner	1728	1510
Total Unique Tags Dispensed by Sampling (EF & HP)	861	1357
Total Unique Tags that were Cross-trip Recaptures detected by Sampling (EF and HP)	286	423
Total Unique Tags Detected by Sampling (EF & HP)	1147	1780
Total Unique Tags Shared in Common between Sampling (EF & HP) and Fish Scanner (union)	151	649
Proportion of total tags Shared between Sampling and Fish Scanner	8.7%	43.0%
Total Unique Tags Detected by Sampling (EF & HP) Not Detected By Fish Scanner	996	1131
Total Unique Tags Detected by Fish Scanner Not Detected by Sampling (EF & HP)	1577	861
Total Unique Tags from only Sampling (EF & HP) later Recaptured (=> 1x) by Sampling (EF & HP)	137	368
Total Unique Tags between Sampling and Fish Scanner	2438	2218
Proportion of Unique tags from FS at a species level		
Bluehead sucker	0.5%	0.3%
Flannelmouth sucker	15.0%	54.3%
Humpback chub	75.4%	28.0%
Rainbow trout	1.3%	0.3%
Yellow bullhead	0.2%	
Unknown	7.8%	17.1%
Overall	92.2%	82.8%

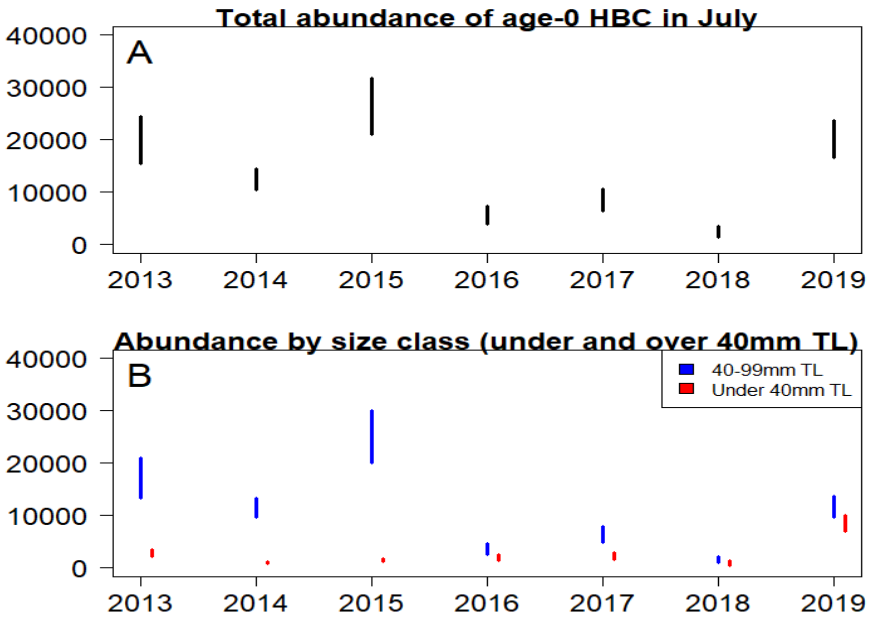


Figure 4. Estimated abundance of age-0 humpback chub (i.e., < 99 mm total length (TL)) during mid-summer sampling trips to the lower 13.6 km of Little Colorado River.

Pre-Monsoon Juvenile Chub Sampling in the LCR

In 2019, monitoring occurred from June 27 to July 8. As in previous years, three teams completed two passes of the LCR using hoop nets, seines, and dip nets. The main focus of the trip was to mark and recapture juvenile HBC to obtain an estimate of population size and outmigration. Accordingly, all HBC > 39 mm TL and < 80 mm TL were given VIE marks that were specific to the trip, gear type (hoop net versus dipnet/seine), and size category (40-59 mm TL or 60-79 mm TL). For other fish, the trips followed the fish handling protocol described in Persons and others, 2015, 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, 3022 humpback chub (40-79 mm TL) were marked with VIE. Population estimates of age-0 HBC were higher for 2019 than for the three previous years (2016-2018; Figure 4A). Importantly, compared to previous years (2013-2018), the size of age-0 fish was much smaller (Figure 4B), indicating either later hatch dates or poorer growth conditions in 2019.

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

Remote Technologies

The LCR MUX is located about 1.7 kilometers upstream of the LCR confluence with the Colorado River. The MUX is comprised of two arrays (*in situ* chains of PIT tag antennas that stretch across the river), an upstream and a downstream array, that continuously detect PIT-tagged fish. The main advantage of this array is that it provides a non-obtrusive method for evaluating movements of fishes between the Colorado River and LCR. In FY 2019, the battery bank powering the downstream array was depleted and not replaced due to the limited functionality of the downstream MUX. The upstream array only had 1-2 antennas working during FY 2019. The current MUX shows very little functionality and there are currently plans to replace the entire MUX with a newer model in 2020. The new MUX has been funded by the Bureau of Reclamation, and Biomark was awarded the contract to build the antennas and help with the installation.

In addition to the MUX, a network of 4-8 single, shore-based antennas were deployed in the LCR in 2017 to help supplement MUX detections. The network antenna design was operational in 2019 and the design consisted of seven antennas – four were placed near 1.3-1.4 river kilometers (rkm) upstream of the LCR confluence with the Colorado River (hereafter the Amazon Island cluster) and three were placed upstream of the waterfall at Boulders camp (rkm 2.0-2.2, hereafter the A-Rock cluster). These antennas are much smaller than the MUX and did not span the entire river width. Rather, they are 123 cm x 61 cm in dimension and are placed parallel to the shoreline. We hope this new design will better help us assess directionality of fish movements, since there is a large waterfall between the two antennas clusters which we

hope will act as an obstacle that deters fish from continuously swimming over both antenna clusters over short time intervals.

During the 2019 spring migration window (Feb 15 – Jun 15), the antenna network detected 5027 unique PIT tags, 3767 of which were HBC. Of these 3767 tags, 383 were detected on both the Amazon Island and A-Rock clusters. Furthermore, of the 383 fish detected on both antenna clusters, 380 were detected on the downstream cluster (Amazon Island) before the upstream cluster (A-Rock), suggesting the antennas were detecting upstream movement. The median time between antenna cluster detections was 76 hours, indicating fish took a little over three days to swim upstream from Amazon Island to above the waterfall at Boulders camp.

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

During fall 2019, two river trips were conducted the USFWS to monitor HBC in the mainstem Colorado River in Marble and Grand Canyons. The first trip (aggregation trip) occurred from September 7-23. A second trip (Diamond down trip) occurred from September 30 to October 8. One objective of the aggregation trips is to continue a long-term relative abundance (catch per unit effort, or CPUE) index of HBC in the known historical aggregation sites. In addition, fish were sampled within three discrete river reaches as part of mark-recapture studies; these being the JCM-west (Fall Canyon) site near Pumpkin Spring, downstream of Diamond Creek near Bridge City, and near 250 mile. The second Diamond down trip functioned as a recapture event for the Bridge City reach and the reach near 250 mile. These trips employed baited hoop nets and submersible antennas as sampling gear.

Since 2006, there have been increases in HBC CPUE at most aggregations, as well as at some non-aggregation sites. There has also been a dramatic increase in HBC catch in western Grand Canyon since 2014 (Van Haverbeke and others, 2017). Because of this, and because of an increasing interest in understanding absolute abundances of HBC in the mainstem Colorado River, mark-recapture studies were incorporated into this work in 2017. To this end, USFWS has worked collaboratively with the JCM project (Project G.6) to conduct mark-recapture experiments in the JCM-east and JCM-west reaches. In addition, USFWS conducted mark-recapture studies below Diamond Creek near Bridge City and near 250 mile in 2018 and 2019. In fall of 2018 for example, an estimate of 1,165 humpback chub ≥ 100 mm was generated for a two-mile reach of the Colorado River near Bridge City (river mile 236-238), of which 582 were adults ≥ 200 mm. An estimate of 619 flannelmouth sucker ≥ 150 mm was also generated for this same reach.

In fall of 2019, USFWS conducted monitoring in the following historic aggregations: 30-mile, LCR Inflow, Bright Angel, Stephen Aisle, Middle Granite Gorge, Havasu Inflow, and Pumpkin Spring. We conducted mark-recapture experiments at JCM west, Bridge City, and near 250 mile.

Results are forthcoming. In the near future, USFWS plans to compare estimates from JCM-west derived from open models to the estimates reported here for closed models.

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

Sampling occurred near Fall Canyon and consisted of three passes of hoop net captures and night-time electrofishing. Methods for JCM-west were similar to those described for JCM-east (see Project Element G.3). Species composition of catch in JCM-west was comprised mostly of native species, with the highest catch occurring for flannelmouth sucker (15952), speckled dace (14350), bluehead sucker (1664), humpback chub (1621), and unidentified suckers (1). Nonnative catch was comprised of fathead minnow (434), rainbow trout (181), red shiner (10), brown trout (9), carp (9), green sunfish (2), and striped bass (1). Note that native species were more predominant in catch of the JCM-west site compared to JCM-east, the latter of which had very high catch of fathead minnows and rainbow trout. In the JCM-west reach, catch of HBC >79 mm TL was 302 in May, 880 in July, and 379 in October. In addition, the number of HBC issued VIE marks between 40-79 mm TL was 19 in May, 31 in July, and 51 in October. Submersible PIT antennas provided an alternate gear type that was used to supplement electrofishing and hoop netting efforts (Table 1). Sampling efforts from hoop net captures show that all size classes of HBC were present in both JCM-east and JCM-west (Figure 5).

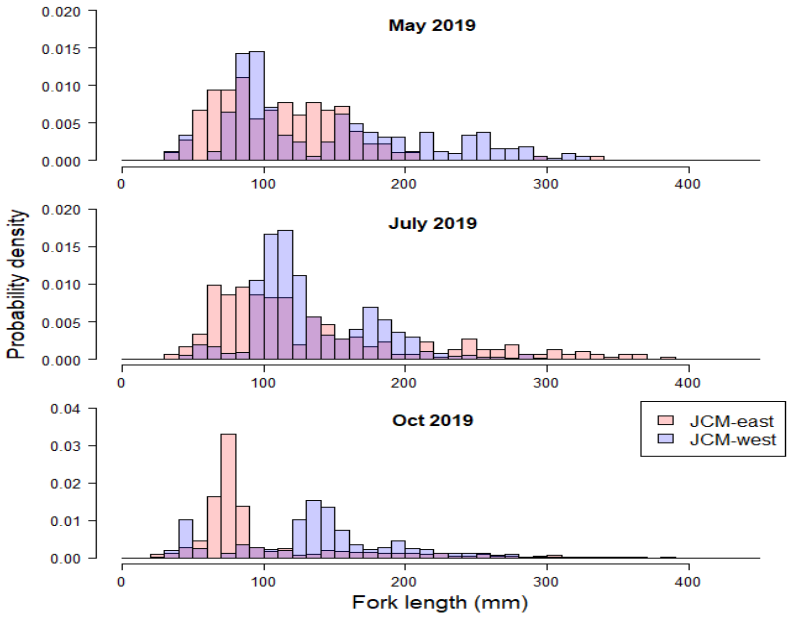


Figure 5. Length-probability histograms for humpback chub captured in hoop nets for three different sampling occasions (May, July, October 2019) at two different sites in the Colorado River (JCM-east, JCM-west).

Project Element G.7. Chute Falls Translocations

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

1) Annually translocate at least 300 juvenile HBC from lower portions of the LCR to upstream of rkm 14.2 (i.e., upstream of Chute Falls).
2) Annually monitor the abundance of HBC 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 2016 Biological Opinion. These monitoring activities also coincide with collaborative efforts with 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 Grand Canyon. In addition, this project provides managers with an annual index of abundance and trend of HBC residing above rkm 13.6.

Translocations

One effort to translocate HBC to the LCR upstream of Chute Falls was conducted in FY 2019. No translocations were conducted in Havasu, Shinumo or Bright Angel Creeks during FY 2019.

Chute Falls:

Efforts to translocate HBC upstream of Chute Falls in the LCR have been ongoing since 2003. To date, approximately 3,470 juvenile (~80-130 mm TL) HBC have been translocated upstream of Chute Falls. Of these, 49 were released above Chute Falls (at rkm 16.2) on October 26, 2018. It is thought that no spring runoff in the LCR during spring 2018 resulted in very poor production of age 0 HBC. That, combined with LCR flooding during the October 2018 collection effort, resulted in an unusually low number of HBC being translocated upstream of Chute Falls. On October 25, 2019, another 307 juvenile humpback chub were released upstream of Chute Falls.

Monitoring

U.S. Fish and Wildlife Service and volunteers conduct an annual monitoring trip upstream of rkm 13.6 in the LCR. The purpose of this effort is primarily to monitor the abundance of HBC that are translocated upstream of Chute Falls but also serves to monitor the abundance of HBC in a small section of river between rkm 13.6 and 14.1, known as the “Atomizer Reach.” 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. From 2006–2009, two pass mark-recapture

population estimates of HBC were conducted upstream of rkm 13.6 in the Atomizer and Chute Falls reaches of the LCR. During these trips, capture probability data was obtained. From 2010–2019, this set of capture probability data were used to annually estimate the abundance of HBC upstream of rkm 13.6 in the Chute Falls and Atomizer reaches. During a trip in May 2019, we estimated there were 349 HBC ≥ 100 mm TL (SE = 44) in the Chute Falls reach. Of these, it was estimated that 263 (SE = 33) were adults ≥200 mm TL (Figure 6). In the Atomizer reach, it was estimated that there were 587 HBC ≥100 mm TL (SE = 26). Of these, it was estimated that 416 (SE = 20) were adults ≥200 mm TL. Results have also indicated unusually rapid growth of translocated fish, and high apparent survival.

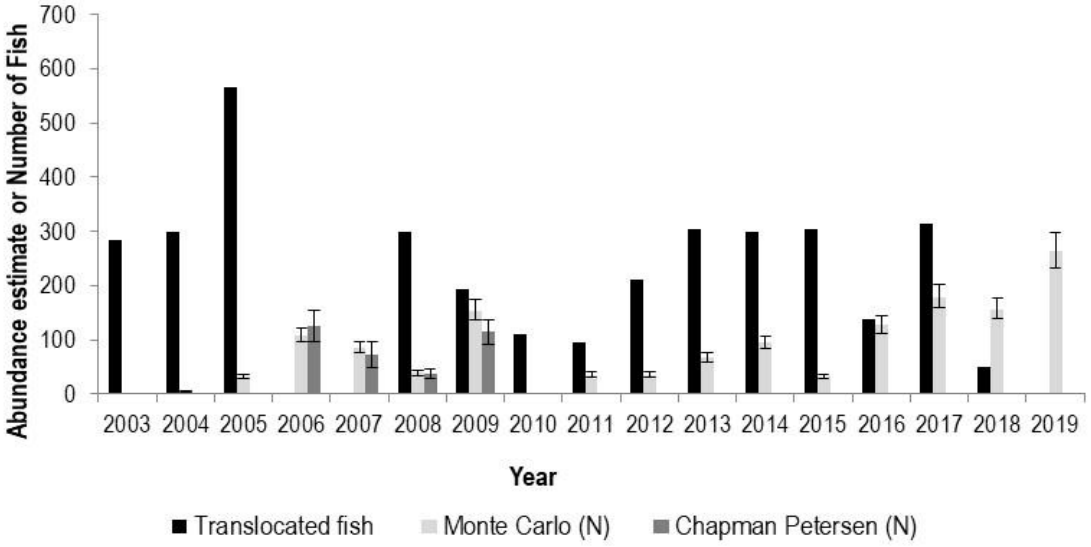


Figure 6. Numbers of juvenile humpback chub that have been translocated to the Chute Falls reach since 2003 (black bars); and abundances of adult humpback chub ≥ 200 mm in the Chute Falls reach (river km 14.1-17.7) estimated with Chapman Petersen method (dark grey bars), and Monte Carlo simulation (light grey bars).

Project Element G.8. Havasupai Translocation Feasibility

This project element is not funded until FY 2020.

Project Element 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 native (particularly age-0) and nonnative fish due to the high capture probability of the sampling gear and ability to easily sample across large spatial extents. Understanding the relationship between backwater catch rates and local population size in collaboration with Project Element G.6 could be particularly insightful.

One backwater seining trip was conducted in 2019 (September 14-27). During this sampling trip, 4478 fish were captured. Native fishes captured included 351 HBC (17-366 mm TL), 2487 flannelmouth sucker, 1326 speckled dace, and 124 bluehead sucker. Nonnative fishes were also captured including 74 fathead minnow, 17 plains killifish, and 5 rainbow trout.

REFERENCES

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

Pearson, K.N., Kendall, W.L., Winkelman, D.L., and Persons, W.R., 2015, Evidence for skipped spawning in a potamodromous cyprinid, humpback chub *(Gila cypha)*, with implications for demographic parameter estimates: Fisheries Research, v. 170, p. 50-59, https://doi.org/10.1016/j.fishres.2015.05.015.

Persons, W.R., Ward, D.L., and Avery, L.A., 2015, Standardized methods for Grand Canyon fisheries research 2015: U.S. Geological Survey, Techniques and Methods, book 2, chapter A12, 19 p., http://pubs.er.usgs.gov/publication/tm2A12.

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.

Yackulic, C.B., Dodrill, M.J., Dzul, M.C., Sanderlin, J., and Reid, J., *in review*, A need for speed in Bayesian population models—A practical guide to marginalizing and recovering discrete latent states: Ecological Applications.

Yackulic, C.B., Yard, M.D., Korman, J., and Van Haverbeke, D.R., 2014, A quantitative life history of endangered humpback chub that spawn in the Little Colorado River—Variation in movement, growth, and survival: Ecology and Evolution, v. 4, no. 7, p. 1006-1018, https://doi.org/10.1002/ece3.990.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Presentation	Integrated assessment of ecosystem management and hydropower generation in endangered species recovery	May 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.
Presentation	Environmental drivers of humpback chub population dynamics in the Colorado River and Little Colorado River.	Sept 2019		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.
Presentation	Combining mark-recapture and PIT antenna detection data to assess ecological drivers of spawning in an endangered desert fish	Oct 2019		Dzul, M.C., Kendall, W., Winkelman, D., and Yackulic, C.B., 2019, Combining mark-recapture and PIT antenna detection data to assess ecological drivers of spawning in an endangered desert fish—presentation: Reno, Nev., Sept 29-Oct 3, 2019, Joint Annual Conference of the American Fisheries Society and The Wildlife Society
Presentation	Using population models of interacting species to support decision makers: Taking the extra steps	Oct 2019		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.
Presentation	A need for speed in Bayesian population models: A practical guide to marginalizing discrete latent states	Oct 2019		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.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Journal article	The trophic ecology of a desert river fish assemblage: Influence of season and hydrologic variability	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, https://doi.org/10.1002/ecs2.2583.
Journal article	Safety in numbers: applying chance-constrained dynamic programming to population viability analysis and adaptive management	FY 2019		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.
Journal article	Maintaining the long-term viability of the humpback chub in the Grand Canyon	FY 2019		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/.
Journal article	An evaluation of sedatives for use in transport of juvenile endangered fishes in plastic bags		FY 2020	Tennant, L.A., Vaage, B.M., and Ward, D.L., *in press,* An evaluation of sedatives for use in transport of juvenile endangered fishes in plastic bags: Journal of Fish and Wildlife Management, online, https://www.fwspubs.org/doi/abs/10.3996/032019-JFWM-016.
Journal article	Effects of disparate water temperatures and food bases on growth rates of humpback chub within the Little Colorado River, Arizona		FY 2020	Stone, D.M., Pillow, M.J., Young, K.L., Van Haverbeke, D.R., and Walters, J.D., *in review*, Effects of disparate water temperatures and food bases on growth rates of humpback chub within the Little Colorado River, Arizona: North American Journal of Fisheries Management.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Journal article	What's in the hump of the humpback chub		FY 2020	Ward, D.L., and Ward, M.B., *in press,* What's in the hump of the humpback chub?: Western North American Naturalist.
Journal article	A need for speed in Bayesian population models: A practical guide to marginalizing and recovering discrete latent states		FY 2020	Yackulic, C.B., Dodrill, M.J., Dzul, M.C., Sanderlin, J., and Reid, J., *in review*, A need for speed in Bayesian population models—A practical guide to marginalizing and recovering discrete latent states: Ecological Applications.
Report	Spring 2019 monitoring of humpback chub (*Gila cypha*) and other fishes above Lower Atomizer Falls in the Little Colorado River, Arizona	Aug 2019		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 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.
Report	Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2018	Jan 2019		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 2019: 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.
Report	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 Sept 17-27 and Oct 15-25, 2019		Dec 2019	Pillow, M.J., 2019, 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 Sept 17-27 and Oct 15-25, 2019: Flagstaff, Ariz., U.S. Fish and Wildlife Service, prepared for U.S. Geological Survey, Grand Canyon Monitoring and Research Center.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Report	Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2019		Jan 2020	Van Haverbeke, D.R., Young, K.L., Stone, D.M., and Pillow, M.J., 2020, *in prep*, 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.
Report	Monitoring humpback chub in the Colorado River, Grand Canyon during fall 2019		May 2020	Van Haverbeke, D.R., Pillow, M.J., and Young, K.L., 2020, *in prep*, 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.

Project H: Salmonid Research and Monitoring

Project Lead	Mike Yard	**Principal Investigator(s)** (PI)	Mike Yard, USGS, GCMRC Kim Dibble, USGS, GCMRC Josh Korman, Ecometric Research Charles Yackulic, USGS, GCMRC Ted Melis, USGS, GCMRC David Rogowski, AZGFD Ted Kennedy, USGS, GCMRC David Ward, USGS, GCMRC Mike Dodrill, USGS, GCMRC Dan Buscombe, USGS, GCMRC Paul Grams, USGS, GCMRC Tom Gushue, USGS, GCMRC
Email	myard@usgs.gov		
Telephone	(928) 556-7377		

SUMMARY

Protection of the endangered humpback chub (HBC) near the Little Colorado River remains as one of the highest priorities of the Glen Canyon Adaptive Management Program (GCDAMP), but a concurrent priority of the GCDAMP is to maintain a high-quality rainbow trout sport fishery upstream of Lees Ferry in Glen Canyon. As such, rainbow trout 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). 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 HBC population. However, ecosystems are dynamic and there has been a large increase in brown trout recruitment upstream of 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.

Project Element H.1. Experimental Flow Assessment of Trout Recruitment

Project 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 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 established 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.

In 2018, a new 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 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 is to assess the effectiveness of GCDAMP policy actions that influence rainbow trout abundance, survival, recruitment, and movement. This type of information has management implications, particularly downstream of Glen Canyon Dam where rainbow 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, some efforts are being made to understand brown trout population dynamics. In addition to rainbow trout, all fishery data are used for informing the model development used for estimating population dynamics in brown trout. Per National Park Service (NPS) guidance, brown trout have been removed from the lowest sub-reach (-4 river mile - sub-reach 1C) and monitored in the upper two less populous sub-reaches. As of 2019, the brown trout removal effort was discontinued in lowest sub-reach 1C. Currently, brown trout are PIT tagged and released unharmed to monitor movement, growth, and to determine variation in capture probabilities, toward improving our understanding of other factors (flows, nutrients temperature, trout density, and size structure) that could be influencing these species in Glen Canyon.

General Overview

In 2019, a total of 46,981 fish (44,113 rainbow trout; 2,584 brown trout; 273 flannel-mouth suckers; 7 green sunfish; 2 common carp, and 2 striped bass) were captured by electrofishing across five seasonal sampling trips conducted in Glen Canyon. Overall, brown trout catch rates (number of fish caught per km shoreline) pooled across all three study sub-reaches has continued to increase (Figure 1). The highest proportion of the catch for brown trout continues to be found in the lowest sub-reach 1C (BNT 2019 catch proportions: 1A – 34%; 1B – 11%; and 1C – 55%). In 2019, brown trout catch rates showed a seasonal increase over the year likely due to changes in the catchability of small fish by electrofishing. Factors that are likely controlling the catchability remain uncertain (Korman and Yard, 2017a); however, fish size, fish density, spawning behavior, and elevated water temperatures, particularly in the fall season are likely factors responsible for the increase in brown trout catchability.

Unlike the previous year, the removal efforts directed at brown trout within the lowest sub-reach 1C near -4 river mile has been discontinued. As previously reported, these removal efforts at this sub-reach or other sub-reaches upstream were considered ineffective at reducing brown trout densities; however, with the deemphasis of removal it enables the TRGD program to sample more effectively and provide resource managers and the GCDAMP with better informed inferences on the status and trends of this problematic species. In particular, the continued tagging effort has resulted in an increase in 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.

Presently, we can report on the relative condition factor for both trout species in Glen Canyon. The recent increase in the spring-summer condition factor strongly suggests that growing conditions are good for rainbow trout (large fish ≥ 275 mm Fork Length (FL)) and are higher now than in past years, particularly when contrasted with the years between 2012 and 2014 (Figure 2). Notably though, the 2016 spring-summer condition factor for large rainbow trout attained the highest condition to date and has since trended downward over the last three

years. One possible explanation for this trend could have been the initial reduction in trout densities following the collapse of the Glen Canyon rainbow trout population in 2014 that resulted in reduced intra-specific competition and by extension a relative increase in the availability of invertebrate prey. Now that the decline in rainbow trout population abundance has stabilized these fish have grown and are recruiting into the population. With the increase in size and overall biomass the demand for invertebrates may be increasing relative to prey availability. Nevertheless, the current condition factor for rainbow trout remains above the relative average since 2012.

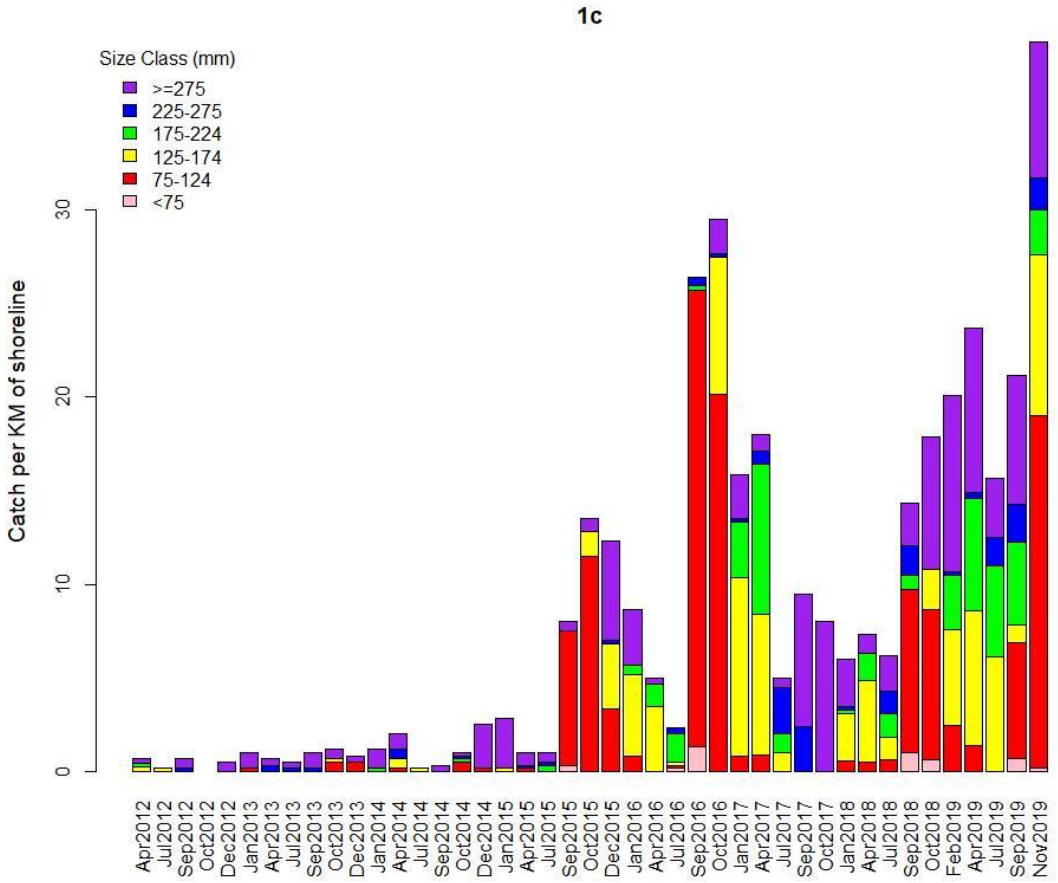


Figure 1. Brown trout seasonal catch rates (number of fish caught per km of shoreline) are based on electrofishing in Reach 1C, Glen Canyon, AZ. Size classes are assigned by fork length, small (≤ 200 mm), medium (201 – 400 mm), and large (> 400 mm). Brown trout catch rates are based on data from the 1st pass of a multiple-pass mark-recapture study.

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 (Figure 1) and these increases appear to be independent of the factors that led to the collapse of the rainbow trout population (Korman and others, 2017), 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 suggest food resources are being partitioned by the larger sized fish. It is likely that brown trout are subsisting more on fish (rainbow trout) rather invertebrate prey items.

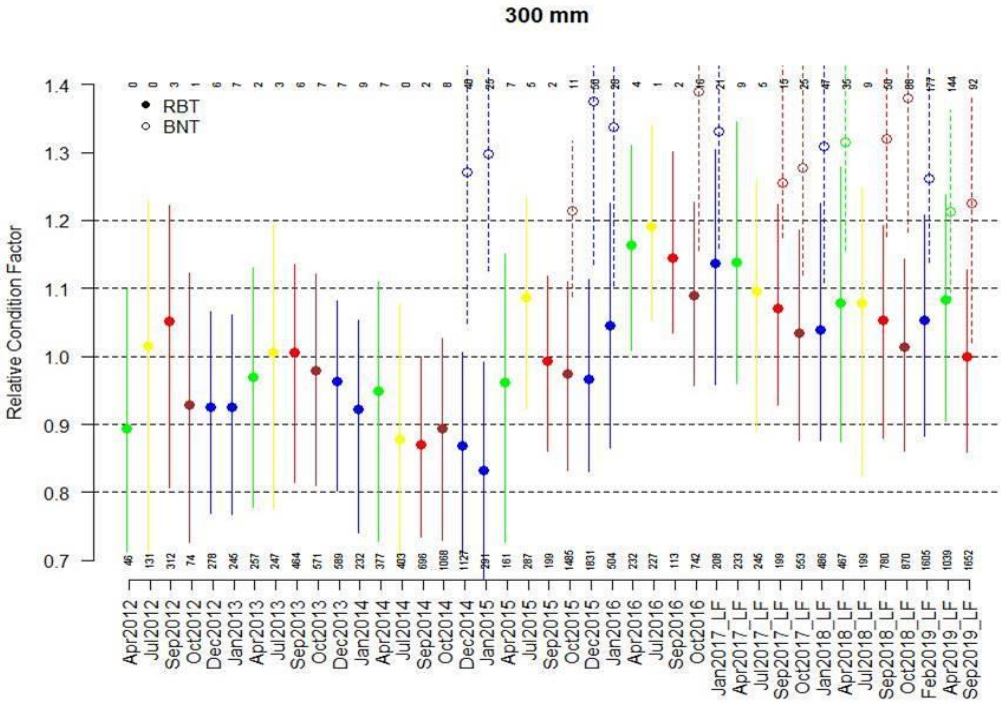


Figure 2. Rainbow trout and brown trout relative condition factor using all electrofishing data collected in Glen Canyon, between April 2012 and September 2019. Points represent the relative condition factor of trout (size range, 300 mm fork length) in Glen Canyon between 2012 and 2018. Condition points show the median value, error bars show 80% credible interval. Seasonal sampling trips are symbolized by color: Green = spring (April), yellow = summer (July), red = late-summer (September), brown = fall (October), blue = winter (December and January). The solid colored points represent rainbow trout and open points represent brown trout.

As proposed in the FY2018-20 TWP, considerable modifications were needed to be made to update the existing Glen Canyon trout population model (Korman and others, 2017). The modeling changes have been accomplished and we are able to report on some of the population dynamics of the rainbow trout population for the three sub-reaches. We are still unable to report on brown trout abundance until we acquire additional recapture information. Results suggest that there is spatial variability in the distribution of rainbow trout abundance (stratified by size-class), abundances among the three sub-reaches are: upstream (1A, Figure 3), middle (1B, Figure 4), and downstream (1C, Figure 5) sections of the study area.

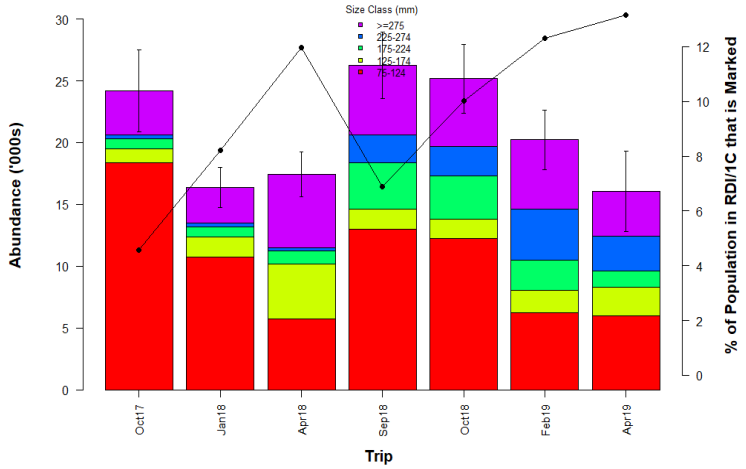


Figure 3. Bar graph, primary y-axis shows rainbow trout abundance estimates (stratified by 5 size-classes) in the upper most sub-reach 1A in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the percentage of marked to unmarked fish in the local population in sub-reach 1A.

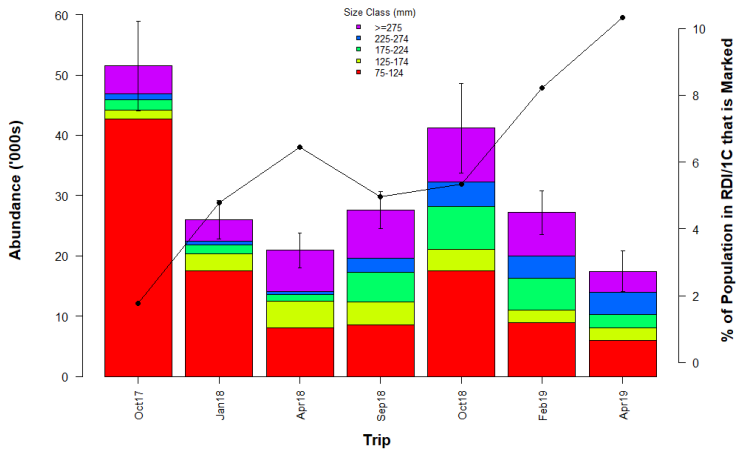


Figure 4. Bar graph, primary y-axis shows rainbow trout abundance estimates (stratified by 5 size-classes) in the middle sub-reach 1B in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the percentage of marked to unmarked fish in the local population in sub-reach 1B.

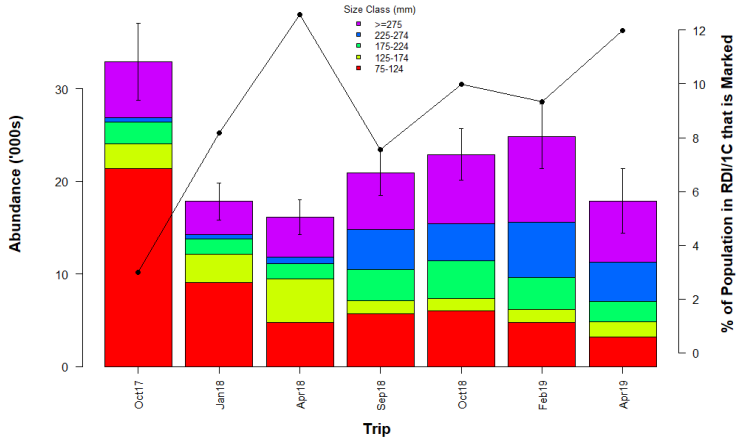


Figure 5. Bar graph, primary y-axis shows rainbow trout abundance estimates (stratified by 5 size-classes) in the lowest sub-reach 1C in Glen Canyon, AZ. Size classes are assigned by fork length, 75-124 mm, 125-174 mm, 175-224 mm, 225-274 mm, and > 275 mm. The secondary line graph represents the percentage 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 some additional years of data collected with and without flow treatments to determine how trout (rainbow trout and brown trout) dynamics in Lees Ferry respond to weekend stable flows designed to improve aquatic insect egg survival (Bug Flows) during spring and summer. Late-spring and summer trout growth will be used as the primary parameter to make comparisons and contrasts as the trout population responds to the flow effects between years. At the earliest, we will begin to report on trout growth in response to Bug Flows after the 2019 data set is collected.

H.1.2. Fall High-Flow Experiments

To date, five fall HFEs have been conducted between 2012 and 2019 (Figure 6). If there is a flow effect 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 flow effect; unfortunately, there are only three years over this time-period without HFEs (2015, 2017, and 2019). Poor fall-winter growth was observed in three consecutive HFE years (2012-2014) across all catchable sized fish. These three consecutive HFE years were accompanied also with 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 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 HFE and low growth immediately after 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 based on weight change between pre- and post-flood periods and between years with and without HFEs 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, 2017 showed no reduction in growth, particularly for the fall and winter seasons. We have yet to complete the data collection effort for 2019 or analyze the growth interval for the other accompanying year without an HFE.

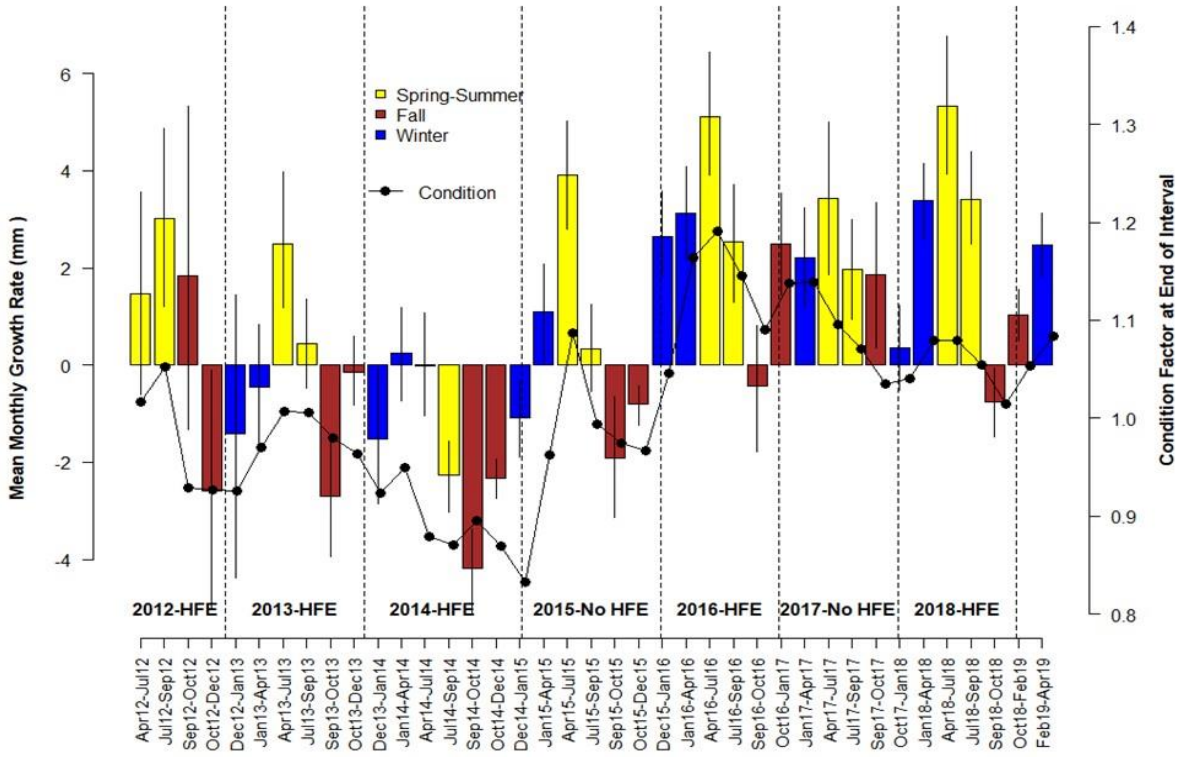


Figure 6. Bar-graph, primary y-axis, is the estimated mean monthly growth rate (g/month, positive or negative) of rainbow trout (300 mm FL) in Glen Canyon between April, 2012 and February, 2019. Monthly growth rates are each estimated across the seasonal interval between sampling trips. Each growth interval has been assigned a color: Spring = yellow; Summer = red, Fall = brown, and Winter = blue.

H.1.3. Spring High-Flow Experiments

No spring High-Flow Experimental treatment has been implemented to date.

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. High levels of recruitment can contribute to poor growth and population collapse which has negative effects on the trout fishery in Glen Canyon (e.g., 2005-06, 2014-15) (Korman and others, 2017). Also, high levels of recruitment in Glen Canyon can increase the number of trout dispersing into Marble Canyon and lead to higher trout abundance at the Little Colorado River with potential negative effects on HBC (e.g., 2007-09, 2011-14) (Korman and others, 2016; Yard and others, 2016). The basic premise of the TMFs is that newly emerged trout (age-0) are small and fragile and are limited to very shallow and low velocity areas near the immediate shoreline. Because of the microhabitat requirements, newly emerged fish are likely to move into habitat inundated by elevated and stable flows (Korman and others, 2011). Under years of high recruitment and once habitat is occupied, if elevated stable flows (flow equalization periods) were to be rapidly reduced age-0 fish would likely be stranded in low-angle habitats. Unfortunately, there are a number of uncertainties that remain about the design of the TMFs. These include questions regarding: peak and withdrawal flow discharge levels, down-ramp rate, flow treatment frequency, quantity of available low-angle habitat, period of flow stability required for colonization, fish-size dependent response, efficacy of action due to compensation, hydropower costs, and others.

The optimization approach that is being used to design and evaluate future TMFs are:

1. Stranding studies literature review, to be completed in FY 2020;
2. Determine the relationships between shoreline slope and discharge and other physical spatial attributes (discussed in June/July 2019 presentation);
3. Conduct GIS and hypsometric analysis to quantify the area of inundation, substrate types, vegetative cover, and velocity, to be completed in FY 2020;
4. A TRGD study to assess annual recruitment of YOY (< 75 mm FL), to be completed in FY 2020; and
5. The development of contingency plans for sampling, should a TMF be implemented in the outlying years of this workplan. These plans include: additional mark-recapture studies, pre- and post-flood response to age-0 trout, and TRGD study to assess annual recruitment of YOY (inter- and intra-annual comparisons with and without a TMF). Final analysis and deliverables are to follow completion of the FY 2018-20 TWP study period. That methodology is discussed in Korman and others, 2009.

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

The primary focus of this research was development of the brown trout model for the brown trout workshop report (Runge and others, 2018). 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 HBC population dynamics to simulate the potential impacts of different management scenarios. In FY 2019, we explored the role that priors played in model output. (Priors is a term commonly used in Baysean statistics, where a prior is defined as the probability distribution of an uncertain quantity/parameter before empirical data is accounted for in the model). Estimates of abundance and vital rates were sensitive to priors because mark-recapture data remains sparse. While mark-recapture data are now becoming available, the limited investment in this item and the diminished capacity for data management and analysis has slowed additional progress.

Project Element 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 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. Projects in this sub-element include: 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.

Building on sample collections from FY 2018, we continued to obtain age-0 brown trout samples in FY 2019 in collaboration with sampling conducted on quarterly TRGD trips with an end goal of estimating hatch and emergence dates via back-calculation for brown trout in the Glen Canyon reach. To date approximately 35 age-0 samples have been collected across six trips. In FY 2020 we will attempt to increase our sample size during spring to summer sampling trips, after which all samples will be processed, and models developed that estimate life history parameters for this species. Due to insufficient sediment inputs HFEs were not implemented in fall 2017 (FY 2018) nor fall 2019 (FY 2020).

Project Element 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. Arizona Game and Fish Department (AZGFD) 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 utilized 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, AZGFD conducted angler surveys to obtain a representative sample of the recreational angling community at Lees Ferry. AZGFD 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

AZGFD completed three monitoring trips in 2019, sampling 120 sites and capturing 3,098 fish (excluding the nonnative sampling). Rare nonnatives captured during our normal monitoring were one bluegill sunfish, two common carp, and 219 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 11-13, 2019, 40 sample sites), one summer electrofishing trip (July 8-11, 2019, 40 sample sites, plus an additional 11 sites for nonnatives), one autumn electrofishing trip (September 23-26, 2019, 40 sample sites, plus an additional 10 sites for nonnatives), angler surveys—six days each month (four weekend days, and two weekdays), and the citizen science project (two-four guides participating, resulting in 32 days of data).

H.4.1. Electrofishing

Rainbow trout continue to dominate the fish community within the Lees Ferry reach, comprising 92.1% of the catch (standard electrofishing), with brown trout comprising 7.07% of the catch. However, for autumn only data, rainbow trout were 88.3% of the catch and brown trout comprised 9.8%. This is a dramatic increase in relative abundance of brown trout compared to all previous years (Figure 7). Rainbow trout have maintained a self-sustaining population since the mid-1990s. Relative abundance, as measured by electrofishing CPUE, has fluctuated greatly since AZGFD began standardized sampling in 1991 (Figure 8). Rainbow trout CPUE was the highest ever recorded in 2011–2012 but declined from 2012 to 2016. Rainbow trout CPUE in 2019 was lower than that observed in 2018 (2.65 vs. 4.15 fish/minute), with most of the fish captured attributable to YOY rainbow trout (< 152 mm TL). Rainbow trout YOY in the fall catch was 49% (compared to 60% in 2018), with a CPUE of 1.36 fish/hour (lower than 2018 at 2.41 fish/minute). After two consecutive years of relatively high CPUE of YOY, a lower CPUE is a positive indicator for this rainbow trout population, as too many YOY fish can lead to too much fish biomass in the system for the available food base.

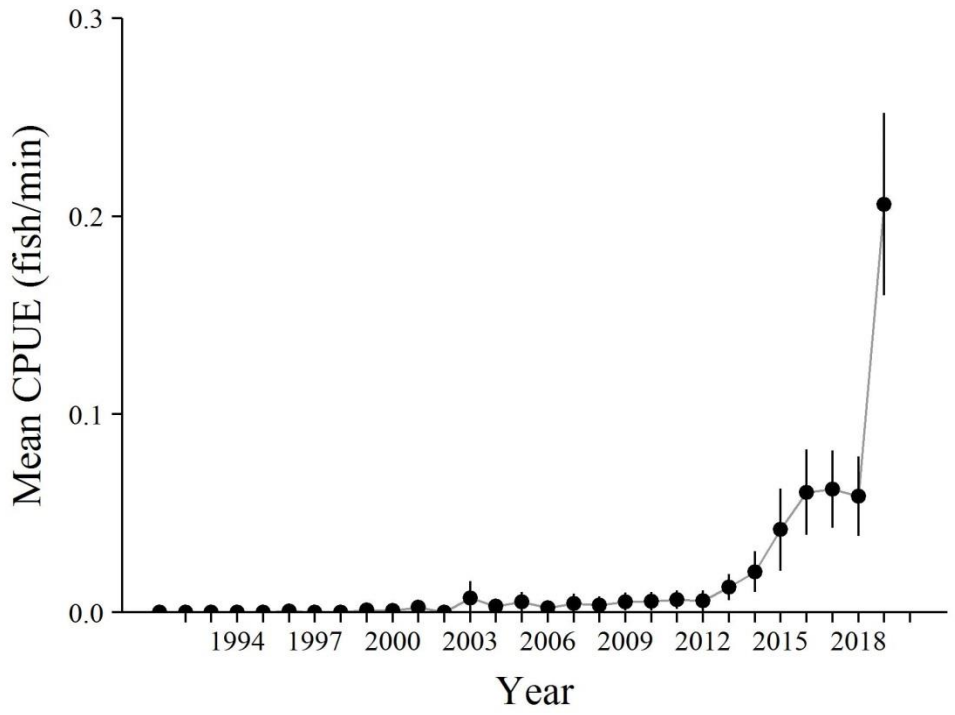


Figure 7. Average catch per unit effort (fish/minute) of brown trout captured during Arizona Game and Fish Department's monitoring at Lees Ferry by year.

The percent of large rainbow trout in the system has declined as has the median size of reproductively active fish. This suggests there were more rainbow trout in the system (based on higher CPUE) than the system was able to maintain during 2011-2014, from a limited food base. 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 2019 has been good with the average condition above 0.90 for all size classes across all sampling trips. During our summer monitoring it was greater than 1.0 for two of the three size classes (152-305 mm total length (TL) and 306-405 mm TL). It was 0.99 for the largest size class (> 405 mm TL).

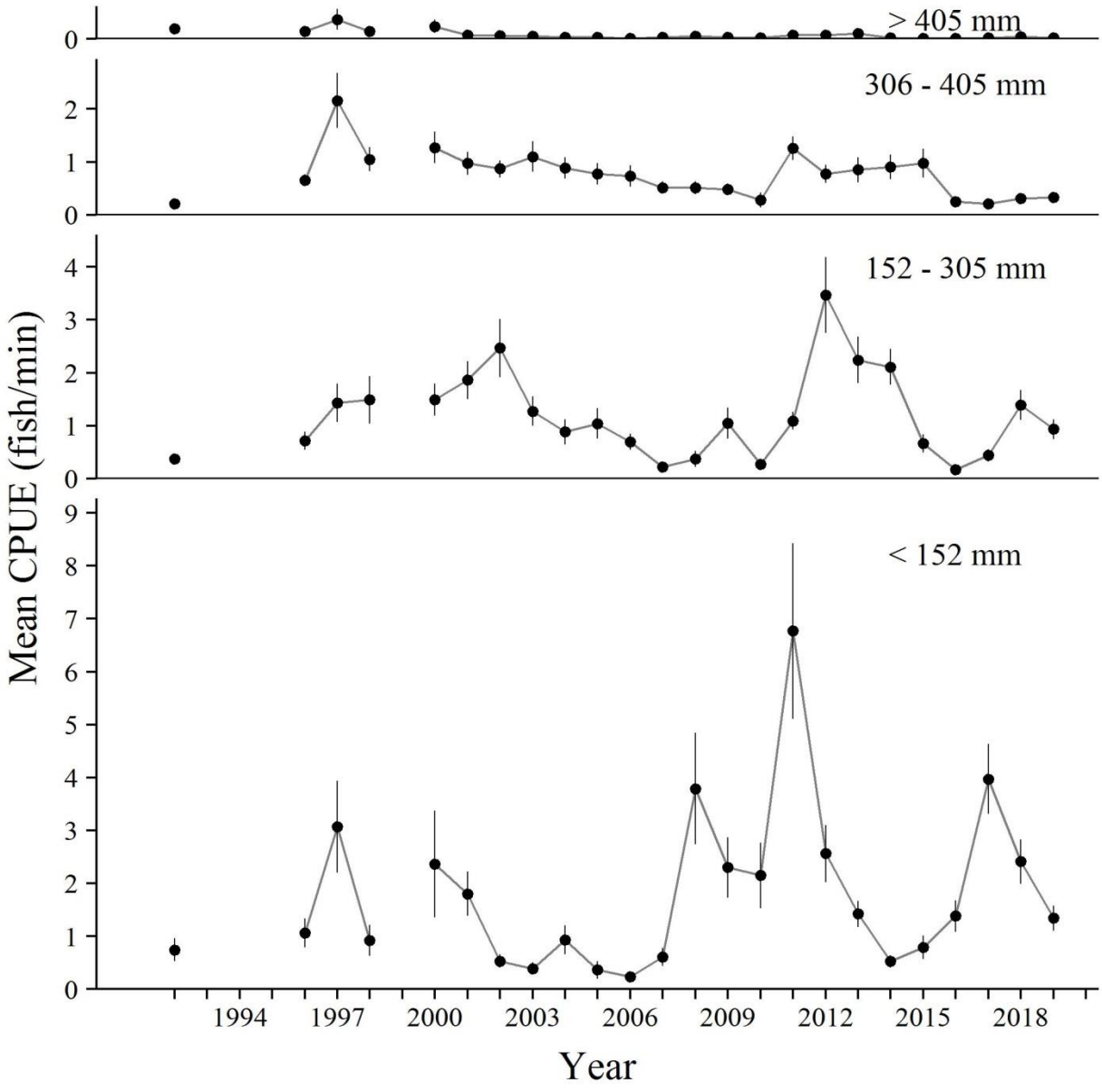


Figure 8. Average catch per unit effort (fish/minute) of rainbow trout at Lees Ferry from Arizona Game and Fish Department's standardized monitoring (electrofishing) by size class and year.

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 2019) we were still collecting angling data and results based on data from January through October (60 creel days, 930 boat anglers, 221 walk-in anglers). Boat angler CPUE and 95% confidence intervals for rainbow trout from January through October was 0.88 fish/hr [0.83, 0.94], while for walk-in anglers it was 0.60 fish/hr [0.39, 0.81]. CPUE in 2019 was essentially the same as last year, and is lower than the AZGFD's goal for the fishery of 1.0 fish/hr. We also saw an increase in angler reported captures of brown trout. Up to the end of October 2019, AZGFD recorded 87 brown trout captured during angler surveys, while in 2018 anglers only captured 47.

As AZGFD is still collecting angler use data, data from 2018 is presented (Figure 9). We estimated a yearly relative angler use of 7,347 anglers in 2018 of which 4,705 (95% CI [4,037, 5,373]) were boat anglers and 2,642 (95% CI [2,213, 3,072]) were walk-in anglers. Angler use was similar to that in 2017 for boat anglers (4,593 95% CI [4,029, 5,158]), and walk-in anglers (2,432 (95% CI [2,065, 2,800]).

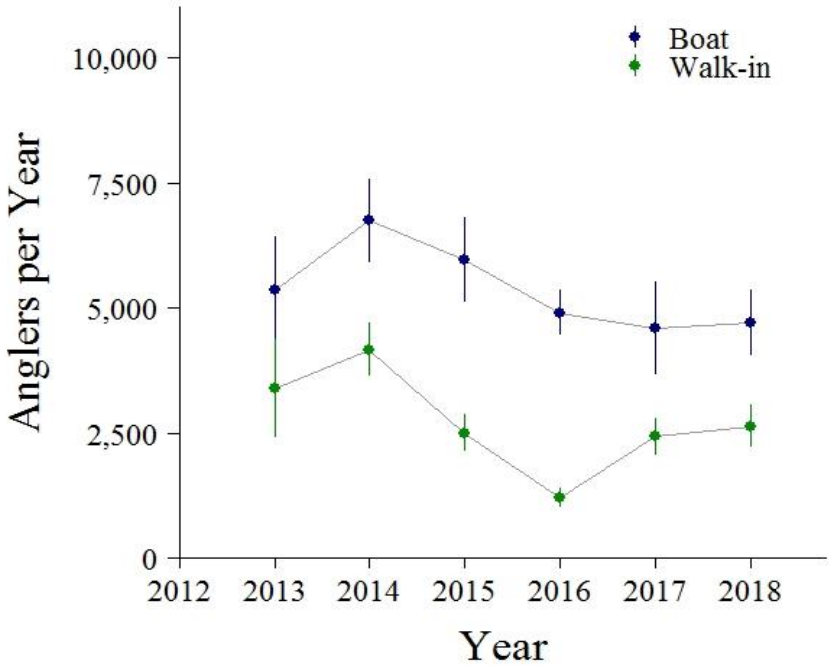


Figure 9. Estimated yearly relative angler use at Lees Ferry from AZGFD angler survey data.

H.4.3. Citizen Science Program

In 2019, three guides participated in the citizen science program, and we received length measurements for 689 rainbow trout captured by 55 anglers over 28 unique fishing trips. Preliminary results show that we are not meeting AZGFD's goals for size structure of fish captured by anglers in the Lees Ferry fishery – only 21% of anglers caught at least one 14-inch rainbow trout per hour, and only four rainbow trout over 20 inches were recorded. The average size of fish measured was 13 inches ± 2.7" (mean ± SD), and the largest fish measured was 20 inches.

REFERENCES

Korman, J., Kaplinski, M., and Melis, T.S., 2011, Effects of fluctuating flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society, v. 140, no. 2, p. 487-505, https://doi.org/10.1080/00028487.2011.572015.

Korman, J., Yard, M., Walters, C.J., and Coggins, L.G., 2009, Effects of fish size, habitat, flow, and density on capture probabilities of age-0 rainbow trout estimated from electrofishing at discrete sites in a large river: Transactions of the American Fisheries Society, v. 138, no. 1, p. 58-75, https://doi.org/10.1577/T08-025.1.

Korman, J., and Yard, M.D., 2017, Effects of environmental covariates and density on the catchability of fish populations and interpretation of catch per unit effort trends: Fisheries Research, v. 189, p. 18-34, https://doi.org/10.1016/j.fishres.2017.01.005.

Korman, J., Yard, M.D., and Kennedy, T.A., 2017, Trends in rainbow trout recruitment, abundance, survival, and growth during a boom-and-bust cycle in a tailwater fishery: Transactions of the American Fisheries Society, v. 146, no. 5, p. 1043-1057, https://doi.org/10.1080/00028487.2017.1317663.

Korman, J., Yard, M.D., and Yackulic, C.B., 2016, Factors controlling the abundance of rainbow trout in the Colorado River in Grand Canyon in a reach utilized by endangered humpback chub: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 105-124, https://doi.org/10.1139/cjfas-2015-0101.

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.

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

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

Yard, M.D., Korman, J., Walters, C.J., and Kennedy, T.A., 2016, Seasonal and spatial patterns of growth of rainbow trout in the Colorado River in Grand Canyon, Arizona: Canadian Journal of Fisheries and Aquatic Sciences, v. 73, no. 1, p. 125-139, https://doi.org/10.1139/cjfas-2015-0102.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Trout management flows—A review of data, research results, and information needs	June 2019	Korman, J., and Yard, M., 2019 Trout management flows—A review of data, research results, and information needs: Phoenix, Ariz., June 11-12, 2019, TWG GCDAMP, Arizona Department of Water Resources.
Presentation	Colorado River ecosystem responses to the 2018 Bug Flow experiment from Glen Canyon Dam	Sept 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.
Report	Status of the Lees Ferry rainbow trout fishery—2018 annual report	FY 2019	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.

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

Project Lead	David Ward	**Principal Investigator(s)** (PI)	David Ward, USGS, GCMRC David Rogowski, AZGFD Kirk Young, USFWS Kim Dibble, GCMRC Charles Yackulic, GCMRC
Email	dlward@usgs.gov		
Telephone	(928) 556-7280		

SUMMARY

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

Goals and Objectives

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 (AZGFD) randomly samples selected reaches and sites throughout the Colorado River in Grand Canyon using boat electrofishing, baited hoop nets, and angling to obtain a representative sample of the fish assemblage. Species composition and relative abundance using catch per unit effort (CPUE) methods can be used to interpret trends in abundance and distribution of native and nonnative fish throughout the Grand Canyon.

Summary of Progress

AZGFD completed three mainstem sampling trips in 2019. On two spring trips (April 3-15, May 18-30) 4,331 fish were captured at 435 electrofishing sites, 2,471 fish in 216 hoop net sets, and 12 fish angling on 25 nights. During the fall sampling trip (Oct 24-28) from Diamond Creek to Pearce Ferry Rapid, 1,256 fish were captured at 72 electrofishing sites, and 1,482 fish in 61 hoop net sets, and eight fish angling on four nights.

Most fish captured were flannelmouth sucker (Table 1; 55% of electrofishing catch, 71% of hoop net catch). AZGFD captured 652 humpback chub in baited hoop nets set from Lees Ferry to Pearce Ferry Rapid. Since monitoring began in 2000, relative abundance of most nonnative species has decreased, and relative abundance of native species has increased (Figure 1, Rogowski and others 2018).

Table 1. 2019 Catch summaries for AZGFD mainstem monitoring.

Native Species		**Nonnative Species**	
Flannelmouth sucker	5,879	Rainbow trout	1,691
Speckled dace	959	Fathead minnow	48
Humpback chub	652	Brown trout	35
Bluehead sucker	259	Common carp	13
Unidentified sucker	1	Red shiner	10
		Striped bass	3
Native Hybrids		Channel catfish	1
Bluehead/flannelmouth	6	Green sunfish	1
Flannelmouth/razorback	3	Yellow bullhead	1
Total	7,759	**Total**	1,803

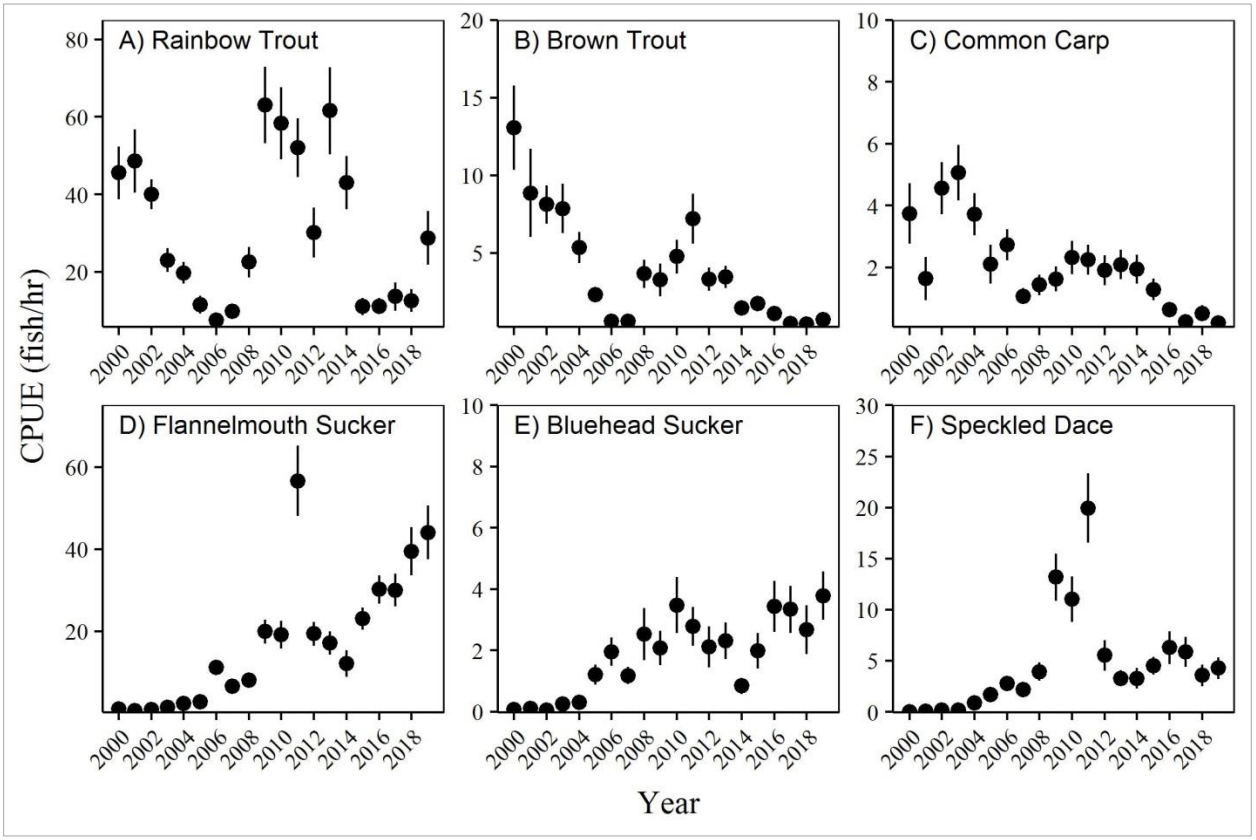


Figure 1. Electrofishing catch per unit effort (CPUE; fish/hour) of nonnative (panels A-C) and native (panels D-F) fishes in the Colorado River in Grand Canyon, 2000-2019.

Asian Fish Tapeworm Monitoring

Asian fish tapeworm monitoring was conducted in conjunction with U.S. Fish and Wildlife Service spring fish monitoring efforts in the Little Colorado River. Forty-one humpback chub (77-302 mm total length (TL)) were held in a collapsible tank on the river bank at Boulders Camp (river kilometer 1.8) and treated with Praziquantel at 6 mg/l for 48-hrs before being released (Ward 2007). Twenty-six tapeworm were detected in 13 individual fish (range 1-11 tapeworms per fish; Figure 2). Relatively low incidence of infestation and the magnitude of infestation per fish from 2015-2019 appears lower than in assessments conducted from 2005-2007.

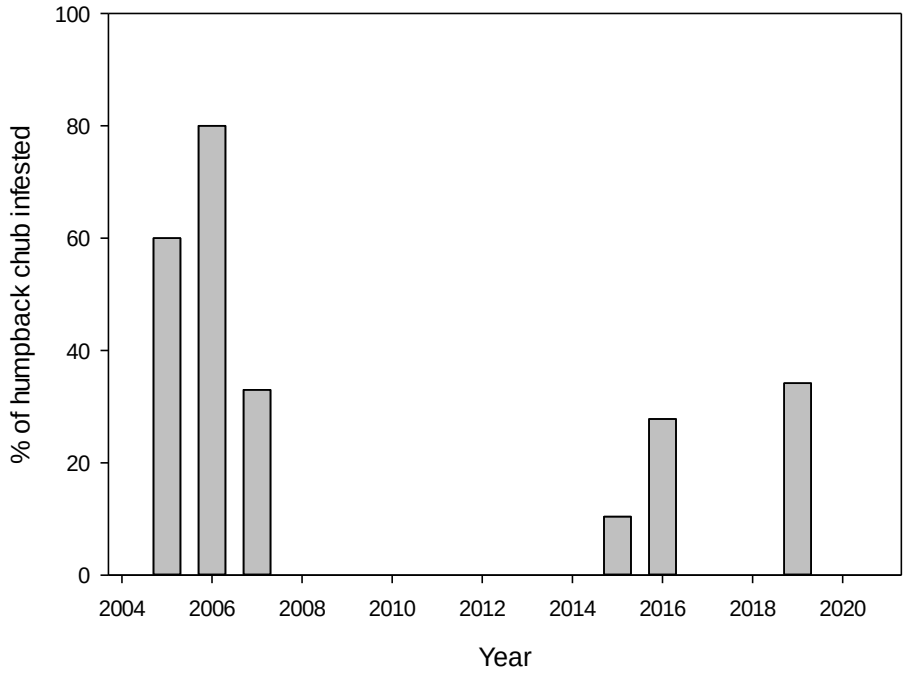


Figure 2. Percentage of humpback chub sampled from 2005-2019 from the Little Colorado River at Boulders Camp that were infested with at least one Asian fish tapeworm.

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) AZGFD 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 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, found in this reach of the Colorado River.

Summary of Progress

During AZGFD's rare nonnative sampling, 61 rare nonnative fish were captured including: 30 common carp, 10 brown trout, 7 green sunfish, 3 walleye, and 1 smallmouth bass. Rare nonnative fish captured during AZGFD's standardized sampling (Project Element H.4) in Lees Ferry consisted of 219 brown trout, 2 common carp and 1 bluegill sunfish.

eDNA Sampling

Water samples to evaluate the use of environmental DNA (eDNA) technology were not collected in 2019 because funding was not approved in the Work Plan for FY 2019. This new technology may allow scientists to detect both the presence and relative abundance of aquatic invasive species moving upstream out of Lake Mead into western Grand Canyon. In FY 2019 we purchased 4 Geopump™ II eDNA sampling pumps with GCDAMP funds in preparation for a May-June 2020 sampling trip. Grand Canyon Monitoring and Research Center (GCMRC) successfully obtained additional non-AMP 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-AMP funding from the Bureau of Reclamation (Reclamation) Phoenix Area Office to fund the cost of the river trip. Reclamation also provided funds directly to the US Forest Service, Rocky Mountain Research Station to fund the cost of sample preparation and eDNA 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. Water samples for eDNA analysis will be collected in FY 2020 to detect the presence and distribution of four species of interest; a potential fifth species will be assessed if funding allows. Due to logistical constraints associated with joining an existing AZGFD fish monitoring trip, we obtained the additional funding to pay for a separate river trip that is longer in length which will allow us to move at our own pace without delaying AZGFD sampling.

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. Our objective is to quantify the relative risks that each warm-water predator poses to native fish. The risk of predation on humpback chub by existing predators such as channel catfish and green sunfish is significant, but impacts have not been quantified. The potential impact of smallmouth bass, which are not yet established in the CRe but may become established, has also not been quantified. Our goal is to

evaluate the relative predation vulnerability of humpback chub to these predatory warm-water species using methods similar to those employed for past trials with rainbow and brown trout (Ward and Morton-Starner, 2015). Standardized methods allow comparison of relative predation risks. These data will allow managers to understand which warm-water invasive fishes are the most detrimental to humpback chub populations so that management efforts can be focused on those species that are the most problematic.

Summary of Progress

In 2019, field efforts focused on marking channel catfish within the Little Colorado River (LCR). We completed four angling trips within the lower 13 km of the LCR (May - June). Eighty-two channel catfish were caught and tagged with Passive Integrated Transponder (PIT) tags with 109 hours of angling effort (0.75 fish/hour). Channel catfish were widely distributed throughout the lower 13 km of the LCR and typically aggregated in deeper pools with large boulders. Although rarely caught with other sampling methods, channel catfish were very susceptible to angling with earthworms. Only two previously tagged fish were recaptured, so no population estimate can be calculated at this time, but the relatively high numbers of fish caught does indicate potential impacts to native fish may be larger than expected. The population is dominated by large adults with the average size being 408 mm TL (Range = 261-630 mm TL; Figure 3). Marking sufficient fish for population estimation may be challenging and require additional angling effort.

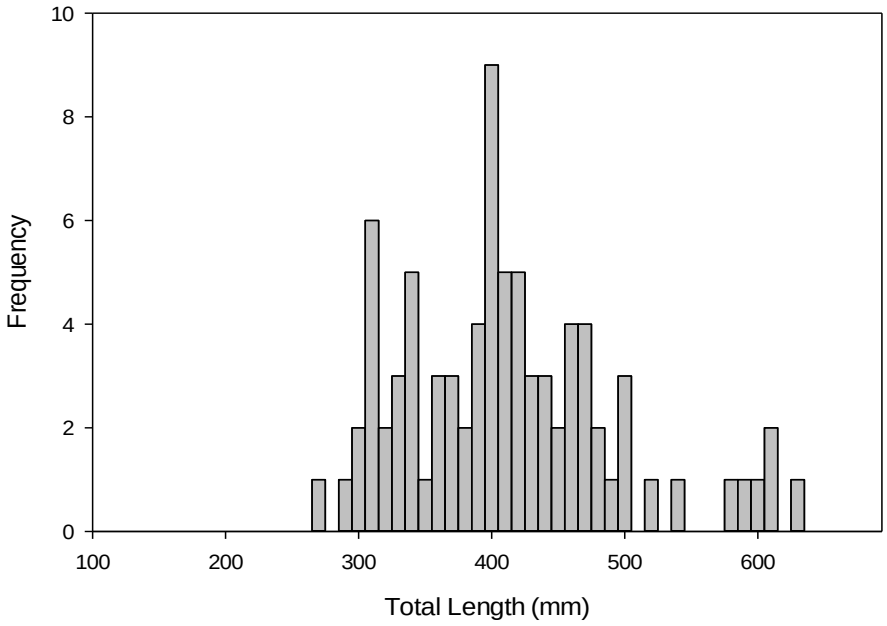


Figure 3. Length frequency histogram for 82 channel catfish angled from the Little Colorado River in 2019.

In FY 2019, laboratory evaluations of predation risk focused on assessing the potential impacts of channel catfish and green sunfish on juvenile humpback chub. Both channel catfish and green sunfish are currently found in the LCR and in the mainstem Colorado River downstream of Glen Canyon Dam. Although their populations numbers are low, they are known to be detrimental to native fish populations in other areas of the Colorado River Basin. In general, green sunfish have been found to be behaviorally more predacious than other predators we have previously tested in laboratory trials and appear to be only limited by gape as far as their ability to capture and consume juvenile humpback chub, as indicated by the steepness of the survival curves (Figure 4).

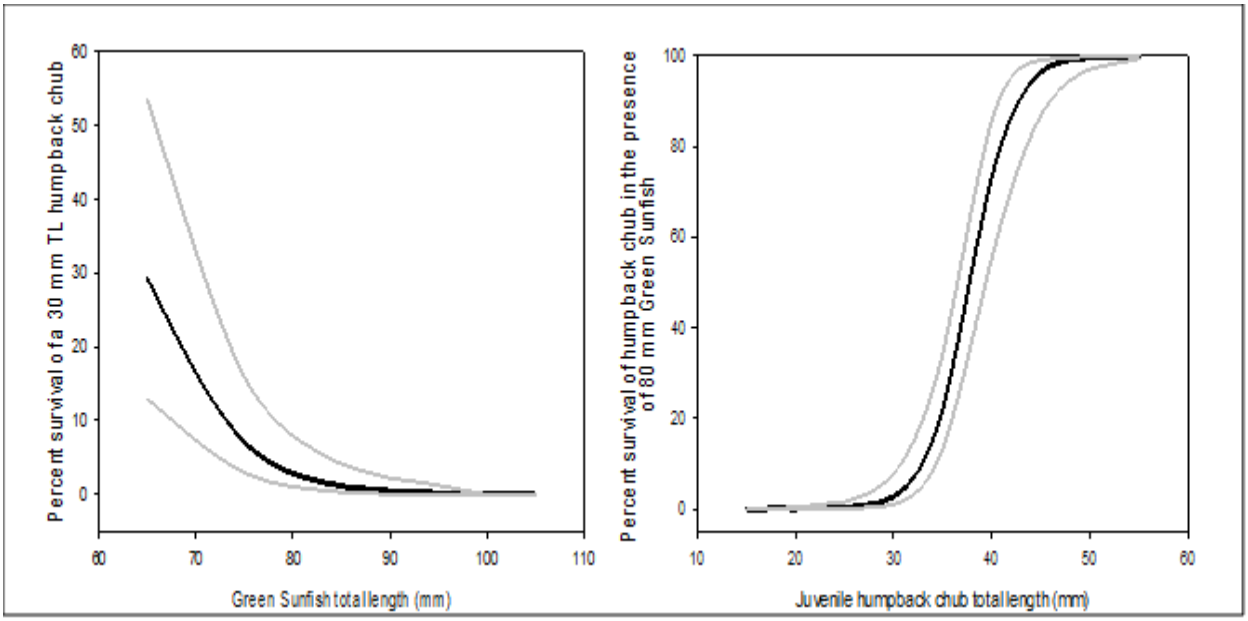


Figure 4. Predicted age-0 humpback chub survival as green sunfish size increases (A), and chub size increases (B). Predicted probability of survival calculated using JMP Prediction Profiler, with a single variable altered in each panel. Results are based on replicated 24-hr laboratory trials. Grey lines represent 95% confidence intervals.

REFERENCES

Rogowski, D.L., Osterhoudt, R.J., Mohn, H.E., and Boyer, J.K., 2018, Humpback chub (*Gila cypha*) range expansion in the western Grand Canyon: Western North American Naturalist, v. 78, no. 1, article 4, https://scholarsarchive.byu.edu/wnan/vol78/iss1/4.

Ward, D.L., 2007, Removal and quantification of Asian tapeworm from bonytail chub using Praziquantel: North American Journal of Aquaculture, v. 69, no. 3, p. 207-210, https://doi.org/10.1577/A06-054.1.

Ward, D.L., and Morton-Starner, R., 2015, Effects of water temperature and fish size on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout: Transactions of the American Fisheries Society, v. 144, no. 6, p. 1184-1191, https://doi.org/10.1080/00028487.2015.1077160.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Presentation	Effects of high flow events on warm-water native and nonnative fishes	April 2019		Ward, D.L., 2019, Effects of high flow events on warm-water native and nonnative fishes—presentation: Phoenix, Ariz., April, 2019, Glen Canyon Dam Adaptive Management Program Annual Reporting Meeting.
Presentation	Development of new ammonia-based piscicides for control of invasive aquatic species	Oct 2019		Ward, D.L., 2019, Development of new ammonia-based piscicides for control of invasive aquatic species—Poster presentation: Montreal, QC Canada, Oct 27-31, 2019, 21st International Conference on Aquatic Invasive Species, https://www.icais.org/pdf/abstracts_2019.pdf.
Presentation	Interactions between native and nonnative fishes in Arizona	Nov 2019		Ward, D.L., 2019, Interactions between native and nonnative fishes in Arizona—presentation: Flagstaff, Northern Arizona University, Forestry Department, Ecological Restoration 382.
Presentation	Science of biological threats: Aquatic Invasive Species and Disease	Nov 2019		Ward, D.L., 2019, Science of biological threats—Aquatic Invasive Species and Disease—presentation: Flagstaff, Ariz., Nov, 2019, Southwest Biological Science Center, Ecosystems Management Area executive leadership science strategy meeting.
Journal article	What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?	June 2019		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.
Journal article	Native fish recovery in a highly regulated river	Nov 2019 submitted		Boyer, J., and Rogowski, D.R., *in review,* Native fish recovery in a highly regulated river: submitted to Transactions of the American Fisheries Society.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Journal article	Effects of body size on vulnerability of young of year roundtail chub to predation by smallmouth bass		April 2020	Tennant, L.A., and Ward, D.L., *in prep*, Effects of body size on vulnerability of young of year roundtail chub to predation by smallmouth bass.
Report	Colorado River Fish Monitoring in Grand Canyon, Arizona – 2018 Annual Report	March 2019		Rogowski, D.L., and Boyer, J.K., 2018, Colorado River fish monitoring in Grand Canyon, Arizona—2018 annual report: Phoenix, Ariz., Arizona Game and Fish Department, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 45 p., https://www.researchgate.net/publication/333634628_Colorado_River_Fish_Monitoring_in_the_Grand_Canyon_Arizona-2018_Annual_Report.

Project J: Socioeconomic Research in the Colorado River Ecosystem

Project Lead	Lucas Bair	**Funded Principal Investigator(s)** (PI)	Lucas Bair, USGS, GCMRC Chris Neher, University of Montana John Duffield, University of Montana Michael Springborn, UC Davis Charles Yackulic, USGS, GCMRC
Email	lbair@usgs.gov		
Telephone	(928) 556-7362		

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 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.

This project addresses the tribal, humpback chub, 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 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."

Project Element 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. 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 2016 national valuation study for use in a tribal setting. 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, and 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, in 2019 we implemented surveys on the Navajo Nation and with the Hualapai Tribe. 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 regulating 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 survey section asked respondents to report on general values associated with the Grand Canyon and the Colorado River (two separate questions). The final question asked respondents to share stories, experiences or other important information about the Grand Canyon and Colorado River. Results from the Navajo Nation and Hualapai Tribal surveys will be presented at the Annual Reporting meeting in January 2020, following approval from the Navajo Nation Human Research Review Board and the Hualapai Cultural Center staff.

In 2020 continued engagement with tribal representatives, researchers, and tribal members through presentation to the Navajo Nation Human Research and Review Board, Navajo Nation Chapters that participated in the survey, Hualapai Cultural Advisory Team, and Hualapai Cultural Center staff will occur. Population level surveys with the Hopi Tribe and the Pueblo of Zuni are uncertain in 2020. The Southern Paiute Consortium have indicated that they will not participate in the survey. Continued engagement with the 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 population level surveys with the Hopi Tribe in 2020.

Project Element J.2. Juvenile Chub Monitoring Near the LCR Confluence

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 (Figure 1).

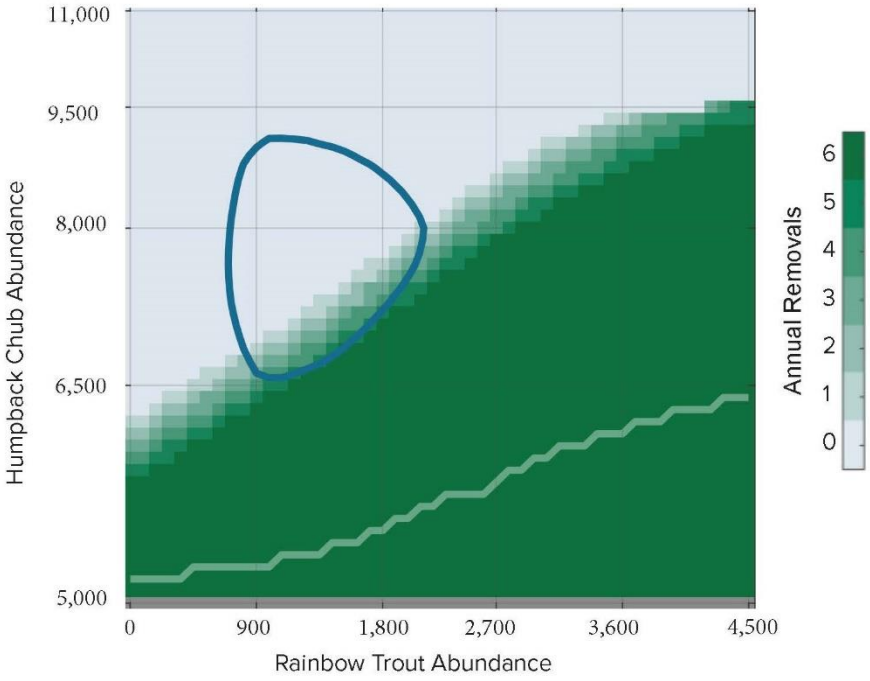


Figure 1. (Adapted from Donovan and Springborn, 2019.) The policy function indicating how many mechanical removals of rainbow trout are cost-effective in a year given the current populations of rainbow trout (horizontal axis) and humpback chub (vertical axis) in the management reach. The light green line spanning the figure from left to right delineates where the probability of remaining above the adult humpback chub abundance goal is not certain over a 20-year time horizon. The blue curve shows the likely rainbow trout and humpback chub abundance (50%) after 20 years under the optimal policy.

The assessment of the value of additional information related to the presence of adult rainbow trout in the juvenile humpback chub monitoring reach and the survival of juvenile humpback chub proved to be substantial. The estimated reduction in cost from improved information, reducing the total number of removals over a 20-year period, was $600,000. This estimated value of information does not consider other benefits of reducing removals over the period.

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). The modeling framework will also allow us to model the effectiveness of management alternatives across future scenarios. For example, ongoing research includes the refinement of the bioeconomic model to assess the effect of U.S. Fish and Wildlife Service Chute Falls translocations on the number of expected trout removals to achieve a population viability goal for adult humpback chub. 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.

REFERENCES

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.

Dean, D.J., and Topping, D.J., 2019, Geomorphic change and biogeomorphic feedbacks in a dryland river—The Little Colorado River, Arizona, USA: GSA Bulletin, v. 131, no. 11-12, p. 1920-1942, https://doi.org/10.1130/B35047.1.

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.

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/.

Van Haverbeke, D.R., Stone, D.M., Coggins, L.G., and Pillow, M.J., 2013, Long-term monitoring of an endangered desert fish and factors influencing population dynamics: Journal of Fish and Wildlife Management, v. 4, no. 1, p. 163-177, https://doi.org/10.3996/082012-JFWM-071.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA	May 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.
Presentation	Tribal preferences for Colorado River water management and the Glen Canyon Dam	Sept 2019	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.
Journal article	Testing the limits of temporal stability: Willingness to pay values among Grand Canyon whitewater boaters across decades	FY 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.
Journal article	Maintaining the long-term viability of humpback chub in the Grand Canyon	FY 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: Geospatial Science and Technology

Project Lead	Tom Gushue	**Principal Investigator(s)** (PI)	Thomas Gushue, USGS, GCMRC
Email	tgushue@usgs.gov		Timothy Andrews, USGS, GCMRC
Telephone	(928) 556-7370		James Hensleigh, USGS, GCMRC

SUMMARY

The Geospatial Science and Technology project provides support to Grand Canyon Monitoring and Research Center (GCMRC) science projects in the realms of Geographic Information Systems (GIS), database development and operation, programming and source control for code, web application development, and other online data resources. Continued efforts in pioneering the Amazon Webs Services (AWS) cloud environment for the Center, expanding on a new Internet of Things (IoT) sensor-to-cloud initiative, and furthering relational database and front-end application development highlight the work being produced from this project. Most work performed within Project 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.

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

General Support to all Projects

The Geospatial Science and Technology project continued to support research and monitoring projects from the FY 2018-20 Triennial Work Plan 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. GIS Administration tasks related to science support included the testing and migration of systems to newer versions of the most commonly used GIS/Remote Sensing software, maintaining licensing information, and/or working with Information Technology (IT) staff to ensure all licenses, software, extensions, add-ons, and custom applications work properly.

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 Amazon Web Services (AWS) cloud platform, or other suitable endpoints. 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 to the cloud where appropriate, in efficient, modern workflows that maintain some consistent elements and yet can be adapted to each project's unique properties.

Project-Specific Support

List of Projects Support:

1. Project B: Sandbar and Sediment Storage
    a. Staff in the Geospatial Project led the way in instituting a new sandbar database and data processing workflow and were responsible for the migration of both the database and sandbar webpage application that now serves these data to the public. It's important to add that this all exists in the Center's new AWS CHS environment for the USGS which has been established and is maintained by the Geospatial Project (Project K).
    b. Redesigned and maintained C# application Survey Accounting CRUD to create, update, delete, display, summarize, catalog and output data from Global Positioning Systems (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 Project B.
2. Project C: Riparian Vegetation Monitoring

The Geospatial project provided updates and training to vegetation monitoring staff on the proper use of the vegetation monitoring database and application interface. The main goal was to assist with data management, analysis, and reporting of vegetation survey data acquired in the field. Prior to this, the data for this project were manually entered into spreadsheets from field data sheets – a workflow that is known to produce many errors, some of which are costly and require time to fix. By continuing to support the database entry workflow that has error-flagging and handling routines built-in, we have been able to greatly improve the process. Additionally, the new vegetation monitoring database will improve the ability to perform analysis across multiple years of data (which were previously aggregated in different spreadsheet files) and more efficiently create reports and web-based analytics on this resource in the future.

3. Project H: Salmonid Research
    a. Continuation of basic geospatial support in the form of river map products and GPS unit preparation in support of field work, basic analysis, and map production for publication and presentation purposes. The GIS project also supports some advance geospatial analysis of Digital Elevation Model (DEM) data to determine slope characteristics of the Glen Canyon Reach.
4. Project I: Warm-Water Native and Nonnative Fish Research and Monitoring
    a. Continuation of basic geospatial support in the form of river map products and GPS unit preparation in support of field work, basic analysis and map production for publication and presentation purposes.

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

Geospatial data management tasks included making updates to server hardware and software, updating existing applications to comply with new security measures, and testing and troubleshooting connectivity to internal systems – such as existing relational databases (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). 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. This included working with other USGS IT entities to resolve web-based issues and improve performance in delivering GCMRC geospatial content online.

Expansion of Cloud Environment Usage for Science Project Support

One 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 USGS Southwest Biological Science Center (SBSC), USGS CHS team members across the country, USGS project leads from other science centers, and contractual partners from the private sector. There were several goals outlined for this past year, with the most notable as follows:

1. Further develop the GCMRC's capacity for working in and building applications for the Amazon cloud environment,
2. Acquiring licenses for and begin working with new data visualization software (Tableau Desktop and Server) that will allow Center staff to connect to a variety of data sources (static files, spreadsheets, relational databases, online services, etc.) and develop custom and advanced data visualizations of their project's information, and

3. Help lead at least one project into using AWS for their data storage and data serving needs.

In FY 2019, 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 continuous 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 the lead GCMRC in developing and managing geoprocessing scripts, web applications and other work involving programming through online source control and versioning platforms, such as USGS GitLab, USGS CHS GitLab, and USGS BitBucket spaces. 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 as technical advisors 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 the online GIS Portal (Grand Canyon Map Portal, https://grandcanyon.usgs.gov/portal/home/index.html) and increased the use of this content delivery system to a wider audience outside GCMRC. This work also involved configuring, testing and publishing new geospatial data sets to the Grand Canyon Map Portal that directly support new science project information and findings.

1. Migration of GCMRC Website to USGS WRET-Compliant Pages

In December 2018, it became apparent that a need existed to migrate the GCMRC website away from a locally-hosted server and into the USGS Web RE-engineering Team's (WRET) cloud-based Drupal environment web hosting platform. This has been a long-standing goal for the USGS, however, it was accelerated due to the USGS Director's new initiative to have all USGS websites migrated by the end of April 2019. Despite this traditionally being a function handled either by the SBSC IT staff or by the SBSC Outreach Coordinator, it was obvious that neither of these entities would be able to complete this task. So the Geospatial project took the lead and migrated content away from the old website (https://www.gcmrc.gov) and into the new USGS-approved web content management system, to which the old website now redirects (https://www.usgs.gov/centers/sbsc/gcmrc/). This work included understanding the

back-end architecture upon which the content management system was built on, designing the web pages, linkages, related content, etc. to be hosted on the new website, and coordinating and communicating with the WRET team on how best to get their platform to work for our Center's unique situation. The new USGS web platform did not have an easy way to define GCMRC as its own entity within the Southwest Biological Science Center, since it is essentially a Center that needs its own home page within another cost accounting Center in the USGS. This work also included identifying and documenting the web redirect links that would be applied through the USGS' National Web Server System (NatWeb) in order for GCMRC's legacy website and web pages to be properly ported to the new content in the cloud. Additionally, this project directed and performed the work to apply the WRET-approved web content to the GCMRC's existing online web applications. All of this work led to a seamless transition for GCMRC's online presence into the larger content management system of the USGS (Figure 1). The new URL for GCMRC's Home Page is located here: https://www.usgs.gov/centers/sbsc/gcmrc.

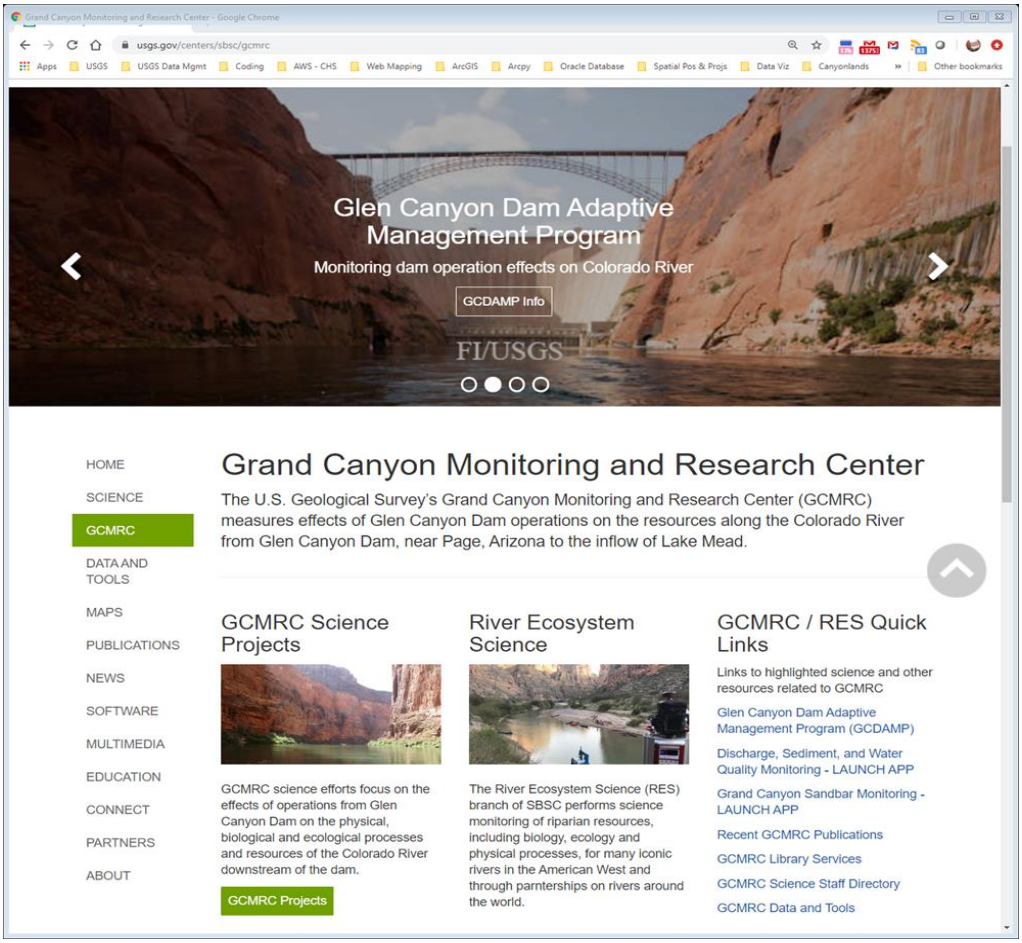


Figure 1. A screenshot of GCMRC's new website and home page. There are several ways to get to this web page, and the original GCMRC URL (https://www.gcmrc.gov) now re-directs to this new location.

2. **System Migrations to New OS**

A major effort in this area was to handle a national system security directive within the Department of the Interior 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 2019, this project was able to rebuild the internal GIS Portal to a new, more advanced system. Work remains on restoring (or redesigning) all content services that existed prior to the migration. The movement of some content was determined to be unnecessary as the data were not current.

3. **New or Improved Web Applications hosted in ArcGIS Online**

Work this year also included leading the effort to improve upon existing web-based services and applications through both the Grand Canyon Map Portal and stand-alone, web-based applications. Additionally, this project has led the efforts to create new, advanced geospatial data exploration tools and applications that are now available as online content. Below is a partial list of just a few new applications now available on ArcGIS Online:

- Predicted Shorelines for High Flows on the Colorado River Application
- Sandbar deposition following the 2018 High-Flow Experiment
- Campsite Atlas Web Application

4. **Grand Canyon Map Portal:** https://grandcanyon.usgs.gov/portal/home/index.html

Work this year also included improving upon existing web-based services and applications through both the Grand Canyon Map Portal and stand-alone, web-based applications. The following is a descriptive list with URLs of new online mapping and data exploration applications now available through GCMRC's website.

5. **UPDATED HFE web page:** https://www.usgs.gov/centers/sbsc/science/high-flow-experiments-colorado-river

We developed a new web page that brings together online maps, data-serving web applications and relevant publications related to past HFE events that is now available through the new GCMRC website. Some of this work was initiated at the end of FY 2018 in preparation for the HFE in November 2018; however, back-end work continued into the first quarter of FY 2019.

6. **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 has been updated in FY 2019 to contain Environmental Systems Research Institute (ESRI) ArcGIS 10.7.1 services. This process involves updating both ArcGIS Server and Portal applications on an external-facing webserver to make available the most current functionality provided by these platforms at the time. Additionally, 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.

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

   The benefit of using ArcGIS online 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 ESRI's ArcGIS Online to reach a wider audience.

8. **IoT Sensor-to-Cloud Data Transmission**

   We have expanded the Center's use of the USGS' CHS environment and provided unparalleled opportunities for GCMRC science staff. Despite having to deal with an unprecedented government shutdown and an extended period of downtime on the sensor-to-cloud work that is part of a larger USGS-wide initiative, we were able to still advance the GCMRC's use of new technologies, including expanding our plans for instituting IoT technology in multiple study sites. This work has made our Center poised

for a renewed interest in IoT technologies and is one of four new pilot projects for the USGS Director's Earth Mapping, Analysis, and Processing (EarthMAP) initiative. Currently, we are able to send data via encrypted text messages using the MQ or "machine-to-machine" Telemetry Transport (MQTT) protocol from a base access point located at Lees Ferry to a cloud brokering service in our CHS-AWS account. The data are sent via cellular transmission from a weather station located adjacent to our base access point at Lees Ferry, and we plan to begin connecting other devices including water quality sensors located in the Lees Ferry vicinity in FY 2020. By leveraging the power of cloud computing, we are able to see data parameters values in near real-time in the form of data packets sent to the cloud broker (Figure 2) and we can build custom data dashboards to track changes in data parameters over time (Figure 3).

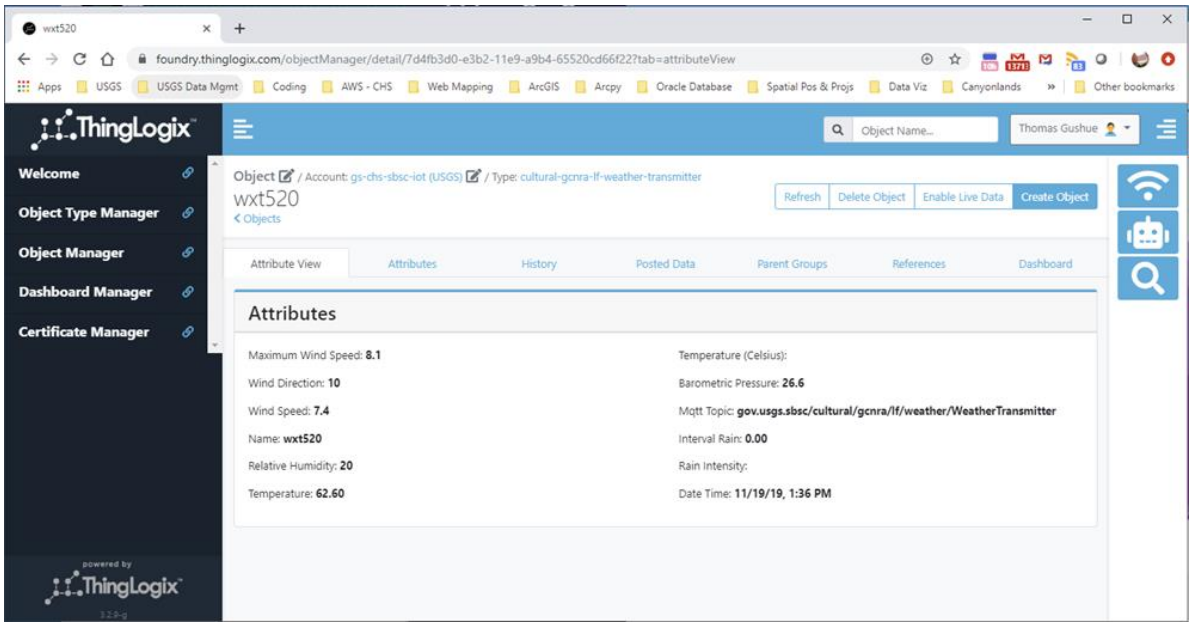


Figure 2. A screenshot of weather station data streaming to AWS IoT cloud environment for the GCMRC's Lees Ferry Internet of Things (IoT) pilot project on November 19, 2019. Data are recorded every 4 minutes and sent via MQ or "machine-to-machine" Telemetry Transport (MQTT) protocol every 15 minutes.

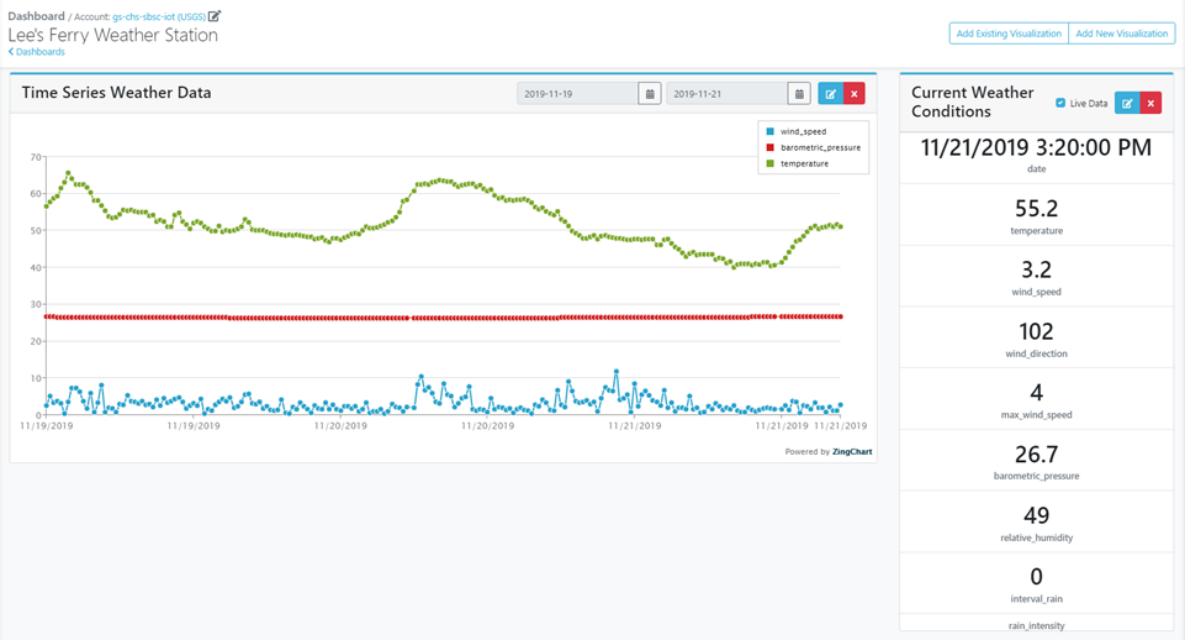


Figure 3. A screenshot of the dashboard functionality available through a third-party data brokering entity called Thinglogix. In FY 2019, the USGS was able to put in place a long-term contract for the Bureau of Reclamation to have exclusive rights for using this service for sensor-to-cloud data transmissions.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Reports, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Web application	Grand Canyon sandbar monitoring	FY 2019 (updated)	Online database and web application: https://www.usgs.gov/apps/sandbar/
New website	Grand Canyon Monitoring and Research Center website	April 2019	New GCRMC website: https://www.usgs.gov/centers/sbsc/gcmrc

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

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

SUMMARY

The remote sensing overflight described in Project L has been postponed and will occur no later than calendar year 2021 so that funding can be applied to other projects with greater priority. A portion of the funds for the overflight (at least $75,000) will be set aside in each year of the FY 2018-20 Triennial Work Plan (TWP) and applied to the overflight in the FY 2021-23 TWP. Reclamation has requested that the geographic extent of the next overflight as a well as the scope of remote sensing work be expanded, particularly in western Grand Canyon and eastern Lake Mead to address conservation measures for razorback sucker as well as other species and resources. This increase in the extent of data acquisition and scope of remote sensing work will further increase the total cost of the next overflight and associated analyses.

The remote sensing projects at Grand Canyon Monitoring and Research Center (GCMRC) were subject to substantial technical staffing reductions in FY 2018-20 due to the budget prioritization described above. Given this and the requested expansion of the geographic extent of the overflight, GCMRC will request additional funding in the FY 2021-23 in order to successfully complete the next overflight and process and serve the imagery in a timely manner.

Project M: Administration

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

SUMMARY

During the Fiscal Year 2019, the budget for this project included the salaries for the librarian, and 80% of a budget analyst. This budget also includes leadership personnel salaries, travel and training for the Chief and Deputy Chief, and part of the salary and travel of one program manager. The vehicle section 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 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 2019 during which they educated youth participants in Colorado River science and directed them in data collection efforts in support of the FY 2018-2020 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).

Project N: Hydropower Monitoring and Research

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

SUMMARY

The overall objective of Project N is to identify, coordinate, and collaborate on monitoring and research opportunities associated with operational experiments at Glen Canyon Dam (GCD) to meet hydropower and energy resource objectives, as stated in the Long-Term Experimental and Management Plan (LTEMP) Record of Decision. Operational experiments include those proposed in the LTEMP Environmental Impact Statement (EIS; e.g., High-Flow Experiments, macroinvertebrate production 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.

Project N: 14.1. Hydropower Monitoring and Research

Evaluating tradeoffs between hydropower generation at GCD and downstream resources is a constant challenge in the Glen Canyon Dam Adaptive Management Program. However, there are limited inquiries into the role of existing hydropower facilities, such as GCD, in minimizing total social and environmental costs. Structural changes in the electricity sector are presenting opportunities for hydropower to play an important role in renewable integration and electricity sector emissions mitigation, reducing total social costs of energy generation. Thus, hydropower can reduce social costs within the electricity sector, and consideration of this potentially restructures costs associated with flow experiments to restore and maintain resources downstream of GCD.

In 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 objective of Project N, 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 is 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 cost 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. 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 is 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. Implementing a proxy experimental flow, or changing from economic dispatch to flat flows, allowed us to compare changes in total power system costs under various fuel price and renewable integration scenarios. Economic dispatch at GCD minimizes production costs of power system generation in the Western Interconnect, constrained by operating rules at GCD (U.S. Dept. of Interior, 2016). Flat flows represent a constant release of water at GCD consistent with monthly release volume requirements.

We used PLEXOS, a production cost model, to estimate variable costs of generation in the Western Electricity Coordinating Council's Transmission Expansion Planning and Policy Committee 2024 baseline (TEPPC, 2014) under economic dispatch and flat flows at GCD. External costs by county associated with CO2, SO2, and NOX power system emissions were estimated following the PLEXOS optimization runs using output from the AP3 Model (Sergi and others, 2019). This allowed us to compare total economic costs under differing operating guidelines and future energy scenarios (Table 1). Note, this is a short run economic analysis and we assumed, confirmed by modeling results, that power capacity requirements were met across future scenarios.

Results indicate that social costs of emissions are significant enough in different future scenarios to offset some changes in production costs under a proxy environmental flow. However, the difference between the social cost of emissions and production costs is dependent on the scenario. Changes in fuel costs (e.g., natural gas) and the integration of different levels of solar generation result in very different economic outcomes (Table 1). While

the proxy experimental flow is not a flow experiment defined in the LTEMP EIS, it is representative of the type of potential changes in total economics costs that may be observed under experimental flows at GCD. Further investigation into the seasonal differences in production and emissions costs under different renewable integration scenarios is warranted.

Table 1. Change in Western Interconnect production and emissions costs with flat flows at Glen Canyon Dam ($2018 dollars in millions).

The baseline production cost is based on the Western Electricity Coordinating Council's Transmission Expansion Planning and Policy Committee 2024 baseline (TEPPC, 2014). Solar scenarios add an additional 700 MW of generation to Arizona. Business as usually, low, and high natural gas prices are $4, $2 and $6 per MMBtu, respectively. Emissions damages are estimated using output from the AP3 Model (Sergi and others, 2019; https://public.tepper.cmu.edu/nmuller/APModel.aspx).

Electricity Sector Scenario	Baseline Production Cost	Change in Production Cost	Change in Emissions Damages			Total Change in Economic Cost
			Carbon Dioxide	Sulfur Dioxide	Nitrogen Oxides	
Business as Usual	$22,445	$4.70	(-$6.61)	(-$0.06)	(-$1.75)	(-$3.73)
High Natural Gas $	$25,700	$16.56	$5.68	(-$0.03)	$0.20	$22.41
High Natural Gas $ with Solar	$25,637	$15.84	(-$3.68)	(-$0.71)	(-$2.58)	$8.87
Low Natural Gas $	$16,693	$2.85	$8.92	$1.61	$6.16	$19.54
Low Natural Gas $ with Solar	$16,661	$4.16	$1.84	$0.30	$1.86	$8.17
Solar	$22,397	$10.25	(-$4.36)	(-$0.33)	(-$2.22)	$3.34

Structural changes in the electricity sector are altering the role of hydropower and how costs associated with experimental flows accrue. Total economic costs of our proxy experimental flow are significantly different when compared to various levels of renewable capacity expansion and fuel costs. Including emissions costs in the analysis significantly modifies total economic costs. The change in emissions costs is primarily due to a change in the quantity of coal fired generation (Figure 1) and subsequent change in sulfur dioxide (Figure 2) and other emissions.

In FY 2020, GCMRC will continue to coordinate with external partners, including Western Area Power and the Department of Energy National Renewable Energy Laboratory, to investigate the implication of renewable energy integration and emissions costs for management of GCD and the maintenance and improvement of downstream resources. This research is also being coordinated with the evaluation of hydropower costs associated with trout management flows and other experiential flows analyzed as part of Project J.2.

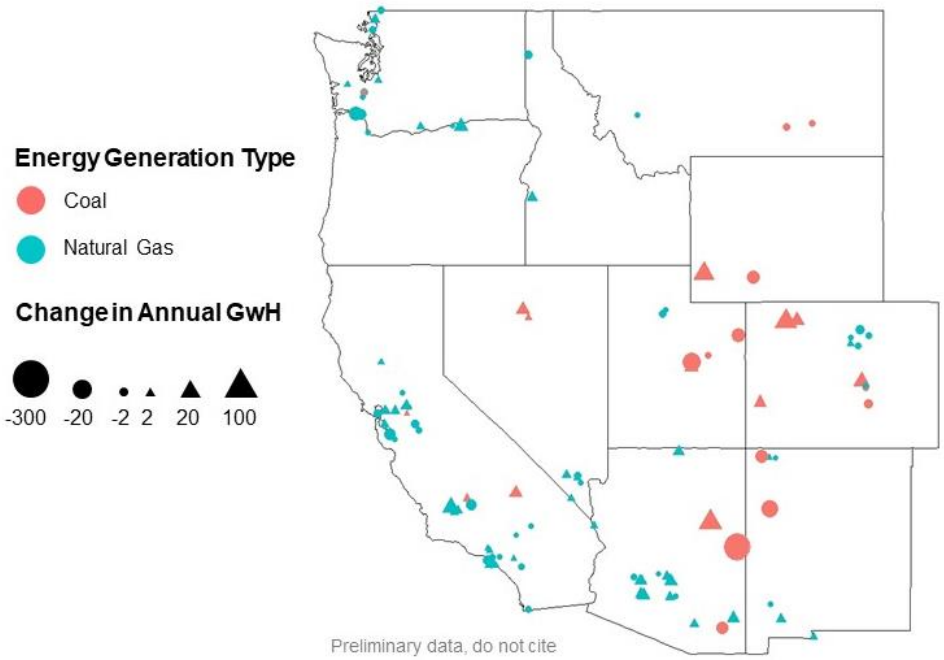


Figure 1. Change in annual generation of coal and natural gas fired generation (GwH) when comparing economic dispatch to flat flows at Glen Canyon Dam under the Western Electricity Coordinating Council's Transmission Expansion Planning and Policy Committee 2024 baseline scenario (TEPPC, 2014).

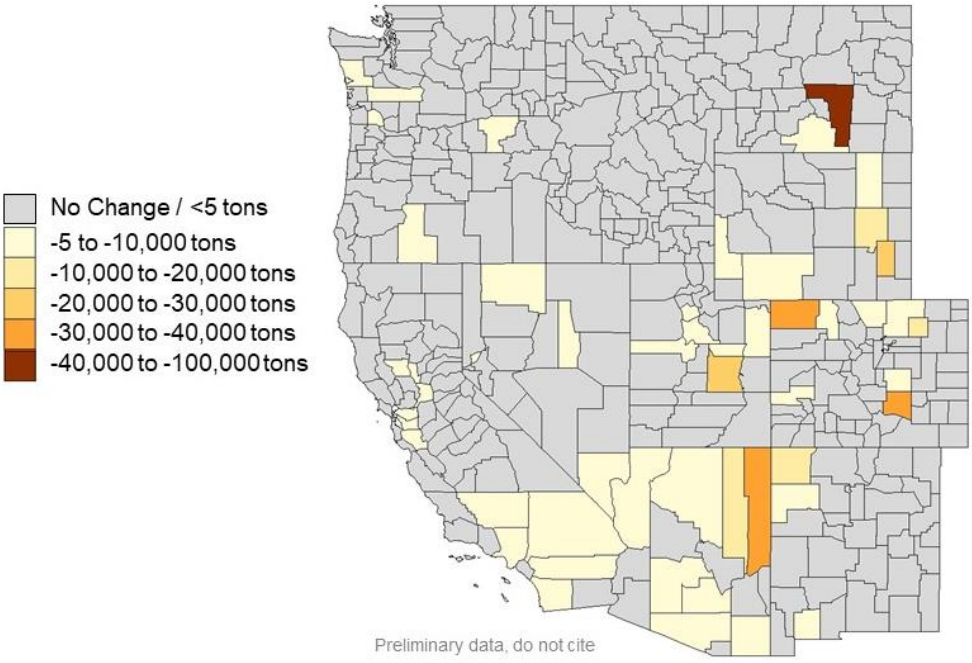


Figure 2. Change in annual sulfur dioxide emissions (tons) by United States county when comparing economic dispatch to flat flows at Glen Canyon Dam under the Western Electricity Coordinating Council's Transmission Expansion Planning and Policy Committee 2024 baseline scenario (TEPPC, 2014).

REFERENCES

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.

Sergi, B., Azevedo, I.L., Davis, S.J., and Muller, N.Z., *in review*, Transboundary health damages of air pollution in the U.S.: Nature Sustainability.

Transmission Expansion Planning and Policy Committee (TEPPC), 2014, 2014 study program by Transmission Expansion Planning and Policy Committee: Salt Lake City, Utah, Western Electricity Coordinating Council, 26 p., https://www.wecc.org/Reliability/TEPPC_2014_StudyProgram.docx.

U.S. Department of 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.

PRODUCTS

(Product order: Presentations, Journal articles, Reports, USGS Series, USGS Data, Web applications)

Type	Title	Date Delivered	Citation, URL, or Notes
Presentation	Integrated assessment of ecosystem management and hydropower generation in endangered species recovery	May 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.
Presentation	Identifying the value of hydropower in the electricity sector and implications for environmental management of rivers	Sept 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.

Appendix 1: Lake Powell Water Quality Monitoring

Program Manager (PM)	Bridget Deemer	**Principal Investigator(s)** (PI)	Bridget Deemer, USGS, GCMRC Nick Voichick, USGS, GCMRC
Email	bdeemer@usgs.gov		
Telephone	360-606-4353		

SUMMARY

In Fiscal Year (FY) 2019, the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC) collected physical, biological, and chemical data and samples from Lake Powell, Glen Canyon Dam (GCD), and Lees Ferry. GCMRC also did some archiving of collected data in an existing Microsoft Access database; however, effort was mainly focused on the development of 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 two years with the potential for funding for three more years. In addition to fulfilling basic monitoring activities, GCMRC contributed to focused sampling before, during, and after the 2018 High-Flow Experiment (HFE) to monitor effects on water column stratification and outflow chemistry. Collaboration with Dickinson College has also resulted in initial analysis of the long-term plankton data set at the Wahweap station, and collaboration with the Environmental Protection Agency has 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.

Project Summary

GCMRC has conducted a long-term water-quality monitoring program of Lake Powell and GCD releases in collaboration with the Bureau of Reclamation (Reclamation) and National Park Service (NPS). This project has been funded entirely by Reclamation from water and power revenues and receives no monetary support from the 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.

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, and 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.

In FY 2019, Reclamation conducted four complete reservoir-wide surveys with involvement from GCMRC (Table 1). In addition, GCMRC conducted six complete forebay surveys and four partial surveys to supplement the quarterly surveys (Table 1). January 2019 was the only month in FY 2019 with no measurements taken owing to annual repair of the Seabird CTD system. GCMRC also maintained two sonde instruments monitoring GCD releases and conducted several methods tests to compare historic and current filtration techniques for inlet water.

Results from laboratory analyses of samples are usually received within two months of collection. While some data were entered into a Microsoft Access database, focus was placed mostly in the development of a SQL-based database that will streamline data import and export. 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 checked twice in FY 2019, once during the October 2018 sampling and once during the June 2019 sampling. 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.

Table 1. Beginning dates and sampling activity for the Lake Powell water-quality monitoring for FY 2019.

Date	Sampling Activity
10/10/18	Forebay, draft tubes, Lees Ferry, and thermistor string
11/2/18	Forebay and Lees Ferry
11/6/18	Forebay and Lees Ferry
11/19/18	Forebay
12/12/18	Quarterly survey
02/07/19	Forebay, draft tubes, and Lees Ferry
03/19/19	Quarterly survey
04/17/19	Forebay, draft tubes, and Lees Ferry
05/16/19	Forebay, draft tubes, and Lees Ferry
06/04/19	Quarterly survey and thermistor string
07/01/19	Forebay, draft tubes, and Lees Ferry
08/01/19	Draft tubes and Lees Ferry
08/22/19	Forebay, draft tubes, and Lees Ferry
09/09/19	Quarterly survey

Analysis Activities

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 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 reported by High Sierra were, on average, 65% of the values reported by the USBR lab. Similarly, water column total phosphorus concentrations reported by High Sierra were, on average, 52% of the values reported by BOR. 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).

Water column stratification and outflow chemistry were monitored before, during, and after the fall 2018 HFE to better understand the extent to which this experimental flow regime affects water quality and limnology. Water quality profiles using the Seabird 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 using the Seabird 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 the sampling conducted this year detected higher soluble reactive phosphorus at Lees Ferry during the HFE (see Figure E.1.2a earlier in this report), an effect that could not be deciphered when detection limits for this analyte were lower.

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) was 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 1). These findings are contained in a manuscript currently under consideration for publication at the journal Limnology and Oceanography.

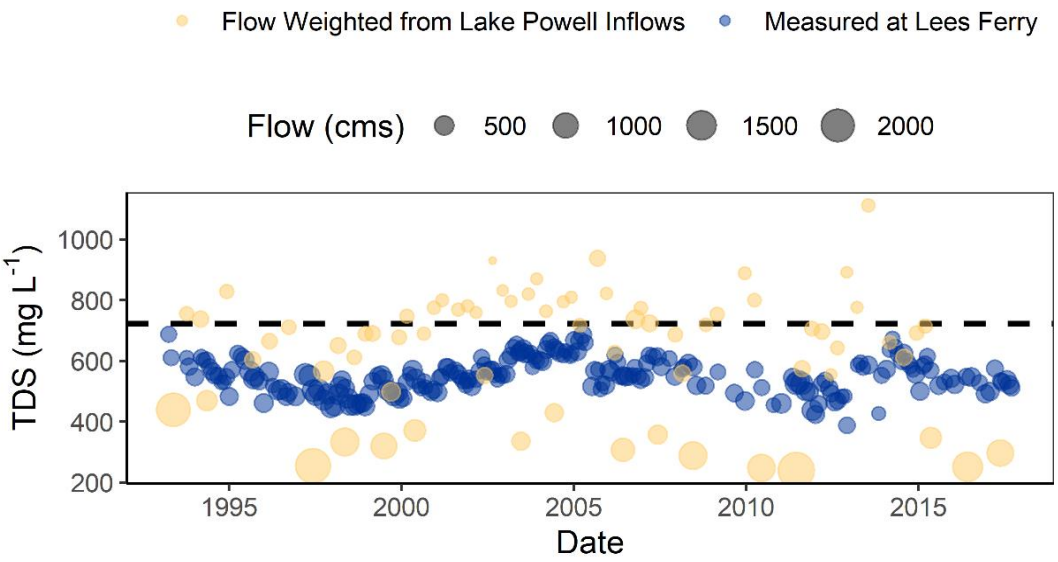


Figure 1. Measured total dissolved solids (TDS) concentrations at Lees Ferry (dark blue, n=223) versus discharge-weighted modeled salinity concentrations from the Colorado River and San Juan River inflow sites (light orange, n=71). TDS is calculated as the sum of the major ions Ca2+, Mg2+, Na+, K+, CO32-, 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).

Current Conditions

Hydrology

Lake Powell received 12.8 million acre feet (maf; 120% of the 1981-2010 average) of unregulated inflow in Water Year (WY) 2019. In comparison, inflow observed in WY 2018 was 4.6 maf (43% of average). The peak reservoir elevation in WY 2019 was 3621.68 feet on August 1, 2019 compared to an October peak of 3628.4 feet in WY 2018. At the end of WY 2019, Lake Powell's surface elevation was 3615 feet (85 feet from full pool) with a storage of 13.3 maf, or 55% of full capacity. This is up from the end of WY 2018 when surface elevation was 3592.3 ft and storage was 11 maf.

Releases for WY 2019 totaled 9.0 maf (the same as for WY 2017 and WY 2018) with operations under the Upper-Elevation Balancing Tier. Operations for WY 2020 will also fall under the Upper Elevation Balancing Tier, with a total projected annual release volume of 8.23 maf and potential for an April 2019 adjustment to equalization or balancing releases.

Glen Canyon Dam Release Temperature

Glen Canyon Dam releases 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 dissolved oxygen event coincided with much lower recruitment and growth in the Glen Canyon rainbow trout fishery (Korman and others, 2012), so the low dissolved oxygen observed in Glen Canyon is of concern. The National Park Service continues to track and monitor the quagga mussel population throughout Lake Powell, mainly by estimating veliger densities in zooplankton tows.

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 (Figure 2). 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 are not accompanied by significant trends in water chemistry. 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 a group of Dickinson students to write up findings into a manuscript for submission at a peer reviewed scientific journal in FY 2020.

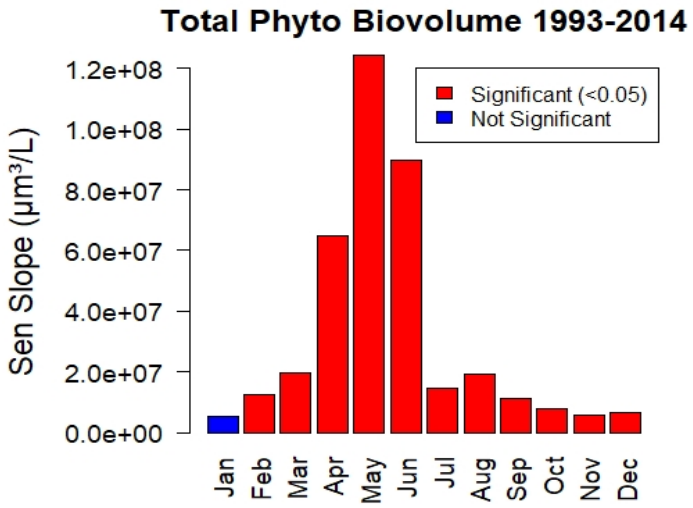


Figure 2. Monthly sen slopes ($\mu m^3\ L^{-1}\ yr^{-1}$) for phytoplankton biomass in the surface waters at the Wahweap station, Lake Powell between 1993 and 2014. We report significant increases in surface water phytoplankton biomass across all months accept January.

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. Efforts are underway to compare 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 area of Lake Powell and the general lack of data from arid region reservoirs. Our single day survey suggests that the per Megawatt-hour (MWh) emission factor for Lake Powell is somewhere around 32 kg CO_2-eq MWh^{-1} at full pool (the majority of which is from CH_4). This emission factor is somewhat higher than that predicted by two global scale models of reservoir greenhouse gas production (18-28 kg CO_2-eq MWh^{-1}, Prairie and others, 2017; Del Sontro and others, 2018), but is significantly lower than a third global model whose results suggested that the potential emissions from Lake Powell could be comparable to the per MWh emissions of natural gas and oil (173-662 kg CO_2-eq MWh^{-1}, Scherer and Pfister, 2016). The emission factor is also dependent on reservoir elevation and the amount of energy that is being generated at any given time. We are working towards a manuscript for the Journal of Environmental Science and Policy that describes this effort.

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 Lake Powell Water Quality Monitoring program over the next year with the potential for funding for up to five years (January 1, 2018 - December 31, 2023). It should be noted that this agreement is separate from the agreement which provides funding under the Glen Canyon Adaptive Management Program. Projected budgets provide funding for a postdoctoral research ecologist ¾ time, a research hydrologist ¼ time, and a technician 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.

REFERENCES

Bureau of Reclamation, 2011, Glen Canyon Dam penstock withdrawal characteristics, 2007-2008: Denver, Colo., U.S. Department of the Interior, Bureau of Reclamation, Middle River Division-Glen Canyon Unit Colorado River Storage Project, Hydraulic laboratory report HL-2011-02, 49 p., https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HL/HL-2011-02.pdf.

DelSontro, T., Beaulieu, J.J., and Downing, J.A., 2018, Greenhouse gas emissions from lakes and impoundments—Upscaling in the face of global change: Limnology and Oceanography Letters, v. 3, no. 3, p. 64-75, https://doi.org/10.1002/lol2.10073.

Hueftle, S.J., and Stevens, L.E., 2001, Experimental flood effects on the limnology of Lake Powell Reservoir, southwestern USA: Ecological Applications, v. 11, no. 3, p. 644-656, https://doi.org/10.2307/3061107.

Korman, J., Martell, S.J.D., Walters, C.J., Makinster, A.S., Coggins, L.G., Yard, M.D., and Persons, W.R., 2012, Estimating recruitment dynamics and movement of rainbow trout *(Oncorhynchus mykiss)* in the Colorado River in Grand Canyon using an integrated assessment model: Canadian Journal of Fisheries and Aquatic Sciences, v. 69, no. 11, p. 1827-1849, https://doi.org/10.1139/F2012-097.

Lovelock, C.E., Evans, C., Barros, N., Prairie, Y., Alm, J., Bastviken, D., Beaulieu, J.J., Garneau, M., Harby, A., Harrison, J., Pare, D., Raadal, H.L., Sherman, B., Zhang, C., Ogle, S.M., Grinham, A., Deemer, B., dos Santos, M.A., Kosten, S., Peacock, M., Zhe Li, Z., and Stepanenko, V., 2019, Wetlands, *in* Gómez, D., and Irving, W., eds., 2019 Refinement to the 2006 IPCC guidelines for national greenhouse Gas inventories: IPCC, chap. 7, v. 4, 7.1-7.54 p., https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., McIntyre, P.B., Kraemer, B.M., Weyhenmeyer, G.A., Straile, D., Dong, B., Adrian, R., Allan, M.G., Anneville, O., Arvola, L., Austin, J., Bailey, J.L., Baron, J.S., Brookes, J.D., de Eyto, E., Dokulil, M.T., Hamilton, D.P., Havens, K., Hetherington, A.L., Higgins, S.N., Hook, S., Izmest'eva, L.R., Joehnk, K.D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E., Leshkevich, G., Livingstone, D.M., MacIntyre, S., May, L., Melack, J.M., Mueller-Navarra, D.C., Naumenko, M., Noges, P., Noges, T., North, R.P., Plisnier, P.-D., Rigosi, A., Rimmer, A., Rogora, M., Rudstam, L.G., Rusak, J.A., Salmaso, N., Samal, N., Schindler, D.E., Schladow, S.G., Schmid, M., Schmidt, S.R., Silow, E., Soylu, M.E., Teubner, K., Verburg, P., Voutilainen, A., Watkinson, A., Williamson, C.E., and Zhang, G., 2015, Rapid and highly variable warming of lake surface waters around the globe: Geophysical Research Letters, v. 42, no. 24, p. 10773-10781, https://doi.org/10.1002/2015GL066235.

Prairie, Y.T., Mercier-Blais, S., and Nahas, R., 2017, The GHG reservoir tool (G-res) technical documentation—UNESCO/IHA research project on the GHG status of freshwater reservoirs—Version 1.12: Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association, 76 p., https://www.hydropower.org/sites/default/files/publications-docs/g-res_technical_document_v1.12.pdf.

Scherer, L., and Pfister, S., 2016, Hydropower's biogenic carbon footprint: PLOS One, v. 11, no. 9, e0161947, p. 1-11, https://doi.org/10.1371/journal.pone.0161947.

Vernieu, W.S., 2009, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964-2013 (ver. 3.0, February 2015): U.S. Geological Survey Data Series 471, 23 p., https://doi.org/10.3133/ds471.

Vernieu, W.S., 2015, Biological data for water in Lake Powell and from Glen Canyon Dam releases, Utah and Arizona, 1990-2009: U.S. Geological Survey Data Series 959, 12 p., https://doi.org/10.3133/ds959.

PRODUCTS

(Product order: Presentation, Journal article, Report, USGS Report, USGS Data, Web application)

Type	Title	Date Delivered	Date Expected	Citation, URL, or Notes
Presentation	Lake Powell significantly reduces the concentration, seasonal variation, and downstream transport of major cations and anions in the Colorado River	June 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, Talk at the Association for the Sciences of Limnology and Oceanography Meeting.
Presentation	Shifting phytoplankton and zooplankton phenology in recent decades in Lake Powell reservoir, southwestern USA	Aug 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.
Presentation	Lake Powell—A critical biogeochemical regulator of downstream ecosystems	Dec 2018		Deemer, B.R., and Yackulic, C.B., 2018, Lake Powell—A critical biogeochemical regulator of downstream ecosystems—poster: December 5, 2018, Rottnest Island, Australia, Poster at the Global Lakes Ecological Observatory Network Meeting.
Journal article	Calcite precipitation in Lake Powell reduces alkalinity and total salt loading to the Lower Colorado River Basin		Dec 2019	Deemer, B.R., E. Stets, and C.B. Yackulic, *in revision*, Calcite precipitation in Lake Powell reduces alkalinity and total salt loading to the Lower Colorado River Basin: Limnology and Oceanography.
Journal article	Are greenhouse gas emissions from Lake Powell significant in a policy decision making context? Results from existing models and an exploratory dataset		June 2020	Are greenhouse gas emissions from Lake Powell significant in a policy decision making context? Results from existing models and an exploratory dataset: To be submitted to Environmental Science and Policy journal.
USGS Data	Calcium, magnesium and total dissolved solids data as well as modeled salinity and mass balance estimates for Lake Powell, 1952-2017		Dec 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, doi: 10.5066/P9A9P44R, (Note: When this data goes online, it will be available at https://doi.org/10.5066/P9A9P44R.).

Tables A and B

Tables A and B present funding by project carried forward from FY 2019 to FY 2020 with short narratives outlining the purpose for which the funds will be used in FY 2020. This information was provided to Reclamation in support of two requests from GCMRC to deobligate funding from the 5-year interagency agreement between the two agencies that expired on September 30, 2019 and reobligate these funds to a new 5-year interagency agreement which was established in August 2019. The majority of these funds are to support the work of GCMRC's cooperators including the U.S. Fish and Wildlife Service, Arizona Game and Fish Department, and Northern Arizona University as outlined in the Triennial Workplan FY 2018–2020. Funding from GCMRC for agreements with cooperators does not typically align with the federal fiscal year due to the timing of Congressional budget approvals and the time it takes for Reclamation to receive funds and then, in turn, transfer those funds to GCMRC. The end of the last 5-year agreement and establishing a new one created the need for the deobligations and reobligations described above since funds transferred to cooperators earlier in FY 2019 could only be used for costs incurred through September 30, 2019.

Table A: Planned Uses of Final Deobligation from Previous 5-Year Agreement

Planned Uses of Final Deobligation from Previous 5-Year Agreement		
Agency/ Cooperator/Contractor	**Project/Activity**	**Amount**
NAU	Project C / Planned carryover to fund a NAU cooperator researching riparian vegetation dynamics in Grand Canyonto provide decision support to NPS efforts to experimentally manage native and nonnative plants. Funding of agreement postponed to FY20 due to delays in receiving USGS and DOI approvals for the cooperative agreement.	$89,000
NAU	Project C / Planned carryover to fund a NAU cooperator to analyze remote sensed data of riparian vegetation to provide decision support to NPS efforts to experimentally manage native and nonnative plants in Grand Canyon. Funding of agreement postponed to FY20 due to delays in receiving USGS and DOI approvals for the cooperative agreement.	$81,773
USGS-GCMRC	Project C / Planned carryover to fund a term plant ecologist position not originally included in the FY20 workplan due to a lack of funds. The ecologist will analyze riparian vegetation data in support of to NPS efforts to experimentally manage native and nonnative plants in Grand Canyon.	$75,100
USGS-GCMRC	Project D / Planned carryover to support completion of the effects of dam operations on geomorphic featues and associated archeological sites in Grand Canyon.	$19,469
USGS-GCMRC	Project E / This project is a new effort that began in the FY18-20 Triennial Workplan to describe the roles of temperature and nutrients as drivers of ecosystem processes in the Colorado River downstream of Glen Canyon Dam and in Grand Canyon. This will help resource managers understand what factors control the aquatic food base and, in turn, fish populations of concern including the endangered humpback chub and rainbow trout, an important sport fish. Sample processing, data entry, and analysis of data collected in FY19 are behind schedule due to a vacant technician position and delays by the USGS Regional Human Resources Office in advertising and hiring that position. This work will now need to be completed in FY20 along with work already planned for FY20. Due to this additional workload, GCMRC proposes to hire an additional technician such that all tasks outlined in the FY18-20 Triennial Workplan are completed by the end of FY20.	$47,342
USGS-GCMRC	Project F / Planned carryover to support processing of aquatic insect samples collected during the 2019 Bug Flows to detemine the effect of this experiment.	$13,995
USGS-GCMRC	Project G / GCMRC is responsible for generating annual population estimates of endangered humpback chub in order for Reclamation to remain in compliance with the 2016 Biological Opinion. Funding for this project supports those efforts. Processing and analysis of humpback chub data collected in FY19 is behind schedule due the retirement of a staff member and delays by the USGS Regional Human Resources Office in advertising and refilling the position. This work will now need to be completed in FY20 along with work already planned for FY20. Due to this additional workload, GCMRC proposes to hire an additional post doc position supported in part by carryover from this project (support will also come from Project H) to help complete all tasks outlined in the FY18-20 Triennial Workplan by the end of FY20.	$101,749
USGS-GCMRC	Project H / GCMRC is responsible for generating information on rainbow trout and brown trout distribution, abundance, production, and other metrics of concern for Colorado River populations of these species downstream of Glen Canyon Dam and in Grand Canyon. Results are provided to Reclamation and the Glen Canyon Dam Adaptive Management Program in support of implementation of the Long-Term Experimental and Management Plan and its Record of Decision. Funding for this project supports those efforts. Processing and analysis of rainbow trout and brown trout collected in FY19 is behind schedule due the retirement of a staff member and delays by the USGS Regional Human Resources Office in advertising and refilling the position. This work will now need to be completed in FY20 along with work already planned for FY20. Due to this additional workload, GCMRC proposes to hire an additional post doc position supported in part by carryover from this project (support will also come from Project G) to help complete all tasks outlined in the FY18-20 Triennial Workplan by the end of FY20.	$82,843
USGS-GCMRC	Project I / Funds will be used to support continued laboratory studies of predation by nonnative warm water fishes on native fishes.	$4,887
ASU	Project J / Funding for ASU cooperator to help evaluate planned NPS incentivised harvest program to control Brown Trout in Glen Canyon. Funding of agreement postponed to FY20 due to delays in receiving USGS and DOI approvals for the cooperative agreement.	$38,000
USGS-GCMRC	Project J / Funds will be used to support continued socioeconomics studies of tribal perspectives and values of resources in Grand Canyon.	$8,946
USGS-GCMRC	Project K / Planned carryover to fund a position that wasn't fully supported in the FY20 workplan due to a lack of funds. This position will help to provide geospatial support for other GCMRC projects and to serve geospatial information and products over the internet to DOI, Reclamation, GCDAMP, stakeholders and the public.	$34,342
USGS-GCMRC	Project L / Planned carryover of funds budgeted in FY18 and FY 19 in support of the remote sensing overflight of Grand Canyon planned for FY21.	$150,000
USGS-GCMRC	Project M / Carryover of funds will be used for the following IT expenses that were planned for FY19, but delayed into FY20: six Life Cycle Replacement Laptops with docking stations, mice, and keyboards ($1,800 each) = $10,800 and one Xen VM server = $9,000.	$19,752
USGS-GCMRC	Logistics / Funds will be used to support GCMRC field operations and to replace damaged equipment as needed. Carryover amount is due to delays in hiring a vacancy created due to a retirement.	$34,398
Ceiba	Logistics / Funds will be used to fully fund the remainder of the first year (through July 2020) of the five-year agreement with Ceiba Adventures to provide professional boat operators and technicians in support of GCMRC field operations. Full funding could not be obligated to this contract due to guidance from Reclamation to not allow spending on obligated funds from IA #R19PG00070 beyond Sept. 30, 2019.	$245,433
	Total	**$1,047,029**

Table B: August 2019 Deobligation

August 2019 Deobligation		
Cooperator/ Contractor	**Project/activity**	**Amount**
NAU	Project B / Long Term Sediment Monitoring in Grand Canyon. Funds were used to supoort continued long-term monitoring of sandbars in Grand Canyon by NAU in FY2020. Specifically, this project involves monitoring and research to measure erosion and deposition of sediment in Grand Canyon. This information is used by the Department of the Interior to inform decisions regarding the operations of Glen Canyon Dam in order to manage sediment resources downstream of the dam. NAU collaborators participate with USGS collaborators in data collection, have lead responsibility for data processing, and work with USGS collaborators on data analysis and reporting. The NAU team has the specialized knowledge and background from many previous years of working on the Colorado River to perform the specific data collection and analyses required for this work. One river trip headed by NAU and which occurred in early FY2020 was supported from this amount.	$448,206
USFWS	Project G / GCMRC is responsible for generating annual population estimates of endangered humpback chub for Reclamation to remain in compliance with the 2016 Biological Opinion. Funding for US Fish & Wildlife Service supports these efforts. USFWS collects data on the distribution, relative abundance, and condition of humpback chub. Funds were used to support USFWS field data collection operations as well as data analysis and reporting related to the humpback chub aggregations in the mainstem Colorado River.	$67,590
USFWS	Project G / GCMRC is responsible for generating annual population estimates of endangered humpback chub for Reclamation to remain in compliance with the 2016 Biological Opinion. Funding for US Fish & Wildlife Service supports these efforts. USFWS collects data on the distribution, relative abundance, and condition of humpback chub. Funds were used to support field data collection operations as well as data analysis and reporting related to the humpback chub the Little Colorado River including translocation efforts.	$262,017
AZGFD	Project H / GCMRC is responsible for generating information on rainbow trout and brown trout distribution, abundance, production, and other metrics of concern for Colorado River populations of these species between Glen Canyon Dam and Lees Ferry. Results are provided to Reclamation and the Glen Canyon Dam Adaptive Management Program in support of implementation of the Long-Term Experimental and Management Plan and its Record of Decision. Funding for Arizona Game & Fish Department (AZGFD) supports these efforts. AZGFD collects data on the distribution, catch rates, and condition of rainbow trout and brown trout in the mainstem Colorado River upstream of Lees Ferry. Funds were used to support field data collection operations as well as data analysis and reporting.	$77,080
AZGFD	Project H / GCMRC is responsible for generating information on native and nonnative fish distribution, abundance, production, and other metrics of concern for Colorado River populations in Grand Canyon. Results are provided to Reclamation and the Glen Canyon Dam Adaptive Management Program in support of implementation of the Long-Term Experimental and Management Plan and its Record of Decision. Funding for Arizona Game & Fish Department (AZGFD) supports these efforts. AZGFD collects data on the distribution and catch rates of native and nonnative fishes in the mainstem Colorado River downstream of Lees Ferry. Funds were used to support field data collection operations as well as data analysis and reporting.	$188,509
Mango	Logistics / Funds will be used to provide additional needed drivers and warehouse help through a contract with Mango Tree Enterprises in support of GCMRC field operations.	$56,000
CEIBA	Logistics / Funds will be used to initially fund the five-year agreement with Ceiba Adventures to provide professional boat operators and technicians in support of GCMRC field operations. The contract with CEIBA required a minimum obligation of $400,000. An initial amount of $256,200 of funding needed to be deobligated from FY19 obligations and immediately reobligated in FY20 in order to meet the required minimum obligation of $400,000 and continue to conduct river operations.	$256,200
	Total	**$1,355,602**
		2,402,631.00