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

Fiscal Year 2018
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) 2018 Annual Accomplishment Report. This report is prepared primarily for the Bureau of Reclamation (Reclamation) to account for work conducted and products delivered in FY 2018 and to inform the Technical Work Group (TWG) of science conducted by GCMRC and its cooperators in support of the Glen Canyon Dam Adaptive Management Program (GCDAMP).

It includes a summary of accomplishments, modifications, results, and recommendations related to projects included in GCMRC's FY 2018-2020 Triennial Work Plan (TWP) for FY 2018[1]. This work is being done to support the 11 resource goals identified in the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) and Record of Decision (ROD) (Table 1). The report also includes budget summaries for each project as well as a separate budget for logistics operations. In addition to project costs, budgets include funds carried forward from FY 2018 to FY 2019.

[1] This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely reporting of current scientific information. 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.

LTEMP Resource Goals

LTEMP Resource Goal	Project(s) Addressing This Goal
Archaeological and Cultural Resources: Maintain the integrity of potentially affected 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: 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 located 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: 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 Colorado River ecosystem 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.
Hydropower and Energy: 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.
Other Native Fish: 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, AZ to Lake Mead.
Recreational Experience: Maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.	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, 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.
Sediment: 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 located throughout the CRe 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, sand transport, and eddy sandbar dynamics.
Tribal Resources: 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 American Indian Tribes preferences for, and values of, downstream resources and evaluating how preferences and values are influenced by Glen Canyon Dam operations.
Rainbow Trout Fishery: Achieve a healthy high-quality recreational rainbow trout fishery in GCNRA and reduce or eliminate downstream trout migration consistent with NPS fish management and ESA compliance.	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: 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 Colorado River ecosystem from Lees Ferry, AZ 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: 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

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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 eight mainstem and 16 tributary sites located throughout the CRe. These data are collected to address the 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 other 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 ROD. Details of this ongoing project (including descriptions of the data-collection locations) are provided in the GCMRC FY 2018–2020 TWP.

Science Question Addressed

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

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

During FY 2018, this question was addressed through:

1) All FY 2018 monitoring data required by this project, including those required to trigger, design, and evaluate the November 2018 HFE, were collected. Processing of all FY 2018 data is complete, and all 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). One exception is laboratory analyses of some of the suspended-sediment data from automatic pump samplers (this task will be completed by the end of February 2019, as is the usual schedule for this project).

2) Maintenance and continued updating of the database and website 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 all 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) Publication of two peer-reviewed interpretive journal articles and six abstracts presented at professional scientific meetings occurred during FY 2018. See product/report list below. In addition to the publication of these papers and abstracts, work progressed during 2018 on other papers identified in the FY 2018–2020 TWP. One paper, entitled "Geomorphic change and biogeomorphic feedbacks in a dryland river: The Little Colorado River, AZ" by David Dean and David Topping, was submitted for publication in the Geological Society of America Bulletin. This paper has been revised and resubmitted to the journal after the initial round of journal peer review. Other FY 2018 papers have been completed, or are nearing completion, and are to be submitted for peer review this winter. These papers include: "Peak-stage indicators of Colorado River floods in Grand Canyon National Park" by Thomas Sabol, Ronald Griffiths, David Topping, Erich Mueller, Robert Tusso, and Joseph 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 Topping, David Rubin, Ronald Griffiths, Paul Grams, Nancy Hornewer, Joel Unema, and others (to be submitted to the American Geophysical Union journal Water Resources Research).

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Online database and web-based applications	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.	ongoing	updated every month	updated every month	http://www.gcmrc.gov/discharge_qw_sediment/ http://cida.usgs.gov/gcmrc/discharge_qw_sediment/
Online realtime database	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.	n/a	hourly	n/a	http://waterdata.usgs.gov/nwis
Abstracts presented at professional meetings	Invited Geological Society of America abstract for 2017 Annual Meeting: On-demand continuous mass-balance sediment budgets for river science and management—Invited presentation made at GSA Annual Meeting in October 2017.	FY 2018	Oct 2017	Oct 2017	Topping, D.J., Griffiths, R.E., Dean, D.J., Grams, P.E., Buscombe, D., and Mueller, E.R., 2017, On-demand continuous mass-balance sediment budgets for river science and management—Invited presentation: Geological Society of American Abstracts with Programs, v. 49, no. 6, https://doi.org/10.1130/abs/2017AM-297045.
	American Geophysical Union abstract for 2017 Fall Meeting: Biogeomorphic feedbacks in the Southwestern USA: Exploring the mechanisms of geomorphic change and the effectiveness of mitigation measures—Presentation made at AGU Fall Meeting in December 2017.	FY 2018	Dec 2017	Dec 2017	Dean, D.J., Diehl, R.M., and Topping, D.J., 2017, Biogeomorphic feedbacks in the Southwestern USA—Exploring the mechanisms of geomorphic change and the effectiveness of mitigation measures: Abstract EP42A-01 presented at

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
					2017 Fall Meeting, AGU, New Orleans, LA, 11-15 Dec, 2017.
	American Geophysical Union abstract for 2017 Fall Meeting: Identification of discontinuous sand pulses on the bed of the Colorado River in Grand Canyon—Presentation made at AGU Fall Meeting in December 2017.	FY 2018	Dec 2017	Dec 2017	Grams, P.E., Buscombe, D., Topping, D.J., and Mueller, E.R., Identification of discontinuous sand pulses on the bed of the Colorado River in Grand Canyon: Abstract EP41A-1825 presented at 2017 Fall Meeting, AGU, New Orleans, LA, 11-15 Dec, 2017.
	Geological Society of America abstract for 2018 Rocky Mountain/Cordilleran Section Meeting: Grain-size limitation of sand storage in the Colorado River in Grand Canyon National Park—Presentation made at GSA Section Meeting in May 2018.	FY 2018	May 2018	May 2018	Topping, D.J., Griffiths, R.E., Rubin, D.M., Grams, P.E., Buscombe, D., Sabol, T.A., and Dean, D.J., 2018, Grain-size limitation of sand storage in the Colorado River in Grand Canyon National Park: Geological Society of America Abstracts with Programs, v. 50, no. 5, https://doi.org/10.1130/abs/2018RM-313931.
	Geological Society of America abstract for 2018 Rocky Mountain/Cordilleran Section Meeting: Geomorphic change and biogeomorphic feedbacks in the Little Colorado River, AZ—Presentation made at GSA Section Meeting in May 2018.	FY 2018	May 2018	May 2018	Dean, D.J., and Topping, D.J., 2018, Geomorphic change and biogeomorphic feedbacks in the Little Colorado River, AZ: Geological Society of America Abstracts with Programs, v. 50, no. 5, https://doi.org/10.1130/abs/2018RM-313857.
	Geological Society of America abstract for 2018 Rocky Mountain/Cordilleran Section	FY 2018	May 2018	May 2018	Grams, P.E., Buscombe, D., Kaplinski, M., and Topping, D.J., 2018,

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
	Meeting: Patterns of riverbed sand-storage change on the Colorado River in Grand Canyon—Presentation made at GSA Section Meeting in May 2018.				Patterns of riverbed sand-storage change on the Colorado River in Grand Canyon: Geological Society of America Abstracts with Programs, v. 50, no. 5, https://doi.org/10.1130/abs/2018RM-314193.
Journal articles and other major pubs.	Journal article: Technical note—False low turbidity readings during high suspended-sediment concentrations.	FY 2018-2020	Mar 2018	Mar 2018	Voichick, N., Topping, D.J., and Griffiths, R.E., 2018, Technical note—False low turbidity readings during high suspended-sediment concentrations: Hydrology and Earth System Sciences, v. 22, p. 1767-1773, https://doi.org/10.5194/hess-22-1767-2018.
	Journal article: How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise.	FY 2018-2020	Aug 2018	Aug 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, online, https://doi.org/10.1002/esp.4489.
	Journal article: Geomorphic change and biogeomorphic feedbacks in a dryland river, submitted to Geological Society of America Bulletin.	FY 2018-2020			Dean, D.J., and Topping, D.J., *in review*, Geomorphic change and biogeomorphic feedbacks in a dryland river: submitted to GSA Bulletin.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Journal articles and other major pubs.	Journal article: Effects of a dam and episodic tributary resupply on sand transport and storage in a supply-limited river, to be submitted to American Geophysical Union journal Water Resources Research.	FY 2018-2020			Topping, D.J., Rubin, D.M., Griffiths, R.E., Grams, P.E., Hornewer, N.J., Unema, J.A., and others, *in prep*, Effects of a dam and episodic tributary resupply on sand transport and storage in a supply-limited river: to be submitted to Water Resources Research.
USGS Open-File Report	Open File Report: Peak-stage indicators of Colorado River floods in Grand Canyon National Park.	FY 2018-2020			Sabol, T.A., Griffiths, R.E., Topping, D.J., Mueller, E.R., Tusso, R.B., and Hazel, J.E., Jr., *in prep*, Peak-stage indicators of Colorado River floods in Grand Canyon National Park: to be submitted as a USGS Open-File Report.

Project A Budget

Project A	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$531,600	$10,000	$80,000	$0	$410,809	$96,702	**$1,129,111**
Actual Spent	$506,784	$5,697	$79,866	$0	$438,620	$92,151	**$1,123,118**
(Over)/Under Budget	**$24,816**	**$4,303**	**$134**	**$0**	**($27,811)**	**$4,551**	**$5,993**
						FY18 Carryover	**$5,993**

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

- Salary surplus due to a reduction in field and laboratory work since there was not a high flow experiment in November 2017.
- Surplus in travel was due to employees not being able to attend a conference they had planned on attending. Original labor estimate was too low for labor to USGS cooperator, so the amount was increased.

Project B: Sandbar and Sediment Storage Monitoring and Research

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SUMMARY

The purposes of this project are to; a) track the effects of individual 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 LTEMP with respect to sandbar condition.

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 2017, processed, and reported at the annual reporting meeting in March 2018. Images from the remote cameras were retrieved in October 2017, April 2018, and October 2018. As of the end of FY 2018, four 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, and 2016. 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 2016 HFE based on digital camera images of sandbars from Lees Ferry to Diamond Creek indicated that there was a substantial gain (deposition) for 24 sandbars (56% of sites), no substantial change for 14 sandbars (33% of sites), and substantial loss (erosion) for 5 sandbars (11% 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 29 and October 16, 2017. 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 annual sandbar survey that occurred before the 2018 HFE and preliminary sandbar-building results from the 2018 HFE based on remote camera images will be presented at the Annual Reporting Meeting in February 2019.

Developments in Sandbar Data Processing and Public Database

In FY 2018, a new workflow and database for processing, analyzing, storing, and disseminating the sandbar monitoring data was implemented. Since 1990, over 1,660 individual topographic and bathymetric surveys have been completed at 45 long-term monitoring sites. Throughout this period, computer software has been used to construct digital surface models of the sites and compute the sandbar area and volume metrics used to evaluate changes over time. However, until recently, those computations were performed manually for each site and results were tabulated in spreadsheets. 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 (www.gcmrc.gov/sandbar).

Sandbar Modeling

Although there is not a specific sandbar modeling project in this work plan, additional progress was made on the preliminary model that was developed during the previous work plan. This is an empirical model that predicts sandbar volume based on streamflow and sediment supply, calibrated to the long-term sandbar monitoring data. Because this model predicts sandbar volume at a daily time-step, it can be used as an intelligent interpolation of sandbar size for the periods between the annual sandbar surveys. We will use this model as one of the tools to evaluate sandbar response to the HFE protocol and present preliminary results from this effort at the 2019 annual reporting meeting.

Analysis of Remote Camera Images

In FY 2018, additional progress was made on the effort to automate the 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 correlate with the annual measurements of sandbar volume.

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

Data Processing and Reporting

In FY 2018, 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 (https://grandcanyon.usgs.gov/portal/home). The data will be available for download on ScienceBase (www.sciencebase.gov) by April 2019.

In a recent publication, Grams and others (2018b) used the channel mapping dataset to demonstrate a method for evaluating the degree of indeterminacy in mass-balance sediment budgets using a signal-to-noise ratio (SNR) analysis. In this analysis, they show SNR is a function of the magnitude of the mass balance and the magnitudes of potential systematic uncertainties associated with measurements and incomplete sampling. This analysis demonstrated that uncertainty resulting from under sampling may approach or exceed that caused by measurement uncertainty and that daily sampling of suspended-sand concentration and repeat mapping of at least 50% of the river segment in Grand Canyon were required to determine the sand budget with SNR > 1. Together, a sand flux and morphological mass balance revealed that sand evacuation 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).

Processing of 2017 Channel Mapping Data and Measurements of Sand Thickness for Absolute Estimates of Sand Storage

In April 2017, topographic and bathymetric data were collected over more than 56 km of the river segment between Tuckup Canyon (river mile (RM) 165)[1] and Diamond Creek (RM 225).

[1] The use of river miles has a historical precedent and provides a reproducible method for describing locations along the Colorado River below Glen Canyon Dam. Lees Ferry is the starting point, river mile 0, with mileage measured upstream, with negative values (–) and downstream, with positive values (+).

Data were processed in FY 2018 and reports and maps are in preparation. Measurements of river bed sand thickness in this reach were collected with a low-frequency sonar. Data were processed in 2018 and the results indicate that approximately 4,630,000 m^3 of sand was stored on the riverbed between RM 166 and 225 of the Colorado River in April 2017. Although this volume is large, it is less than 10 times the average annual sand load. This sand was in storage both in the open channel and in eddies. Because this was the first time this river segment was mapped, it is not known whether the volume of sand was large or small relative to long-term averages. However, the magnitude of the sand reservoir relative to annual sand loads indicates that a few years of low supply and high export could substantially reduce the volume in storage.

Control Network and Survey Support (B.3.)

In FY 2018, the control network was expanded and improved to support current and future river-channel mapping investigations. During 2017 survey efforts between National Canyon and Diamond Creek (RM 166-225), we collected spatial data from 148 control stations, 113 tracking station setups and 27 Global Navigation Satellite System (GNSS) base stations. The local accuracy assessment computed for the entire reach resulted in a horizontal accuracy of 1.9 cm and a vertical accuracy of 2.7 cm at 95% confidence.

In FY 2018 field work, 261 GNSS occupations and 2189 vectors were observed to compute 97 control station positions between Bright Angel Creek and Stone Creek (RM 88-132). These stations will be used as primary reference for future channel mapping efforts and overflight orthoimage collections. The network measurements and results are updated in a current geodatabase and are posted online (https://grandcanyon.usgs.gov/gisapps/ngs_monuments/ngs_gc.html). In addition, 36 stations surrounding Grand Canyon were added as orthometric constraints to reduce the errors in determining elevations from GNSS measurements computed with Geoid 18, more than doubling the number of stations constrained for Geoid 12. The efforts incorporated historical Glen Canyon leveling observations with current GNSS results and assessed control accuracies. The National Geodetic Survey Integrated database (NGSIDB) has been updated with these recent results, which ensures permanent online access to each stations' geodetic coordinates, accuracy, recovery information, and measurement history.

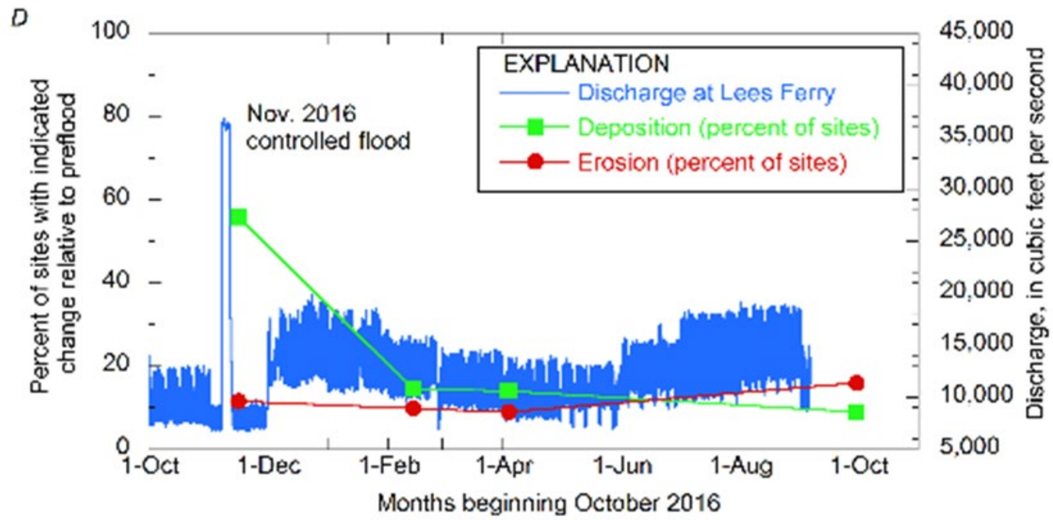

Figure 1. Percent of sandbar sites with deposition (green squares) or erosion (red circles) based on visual estimates of change in sandbar size in remote-camera images from monitoring sites along the Colorado River in Grand Canyon National Park, Arizona, following the November 2016 HFE and Colorado River discharge at Lees Ferry, Arizona (blue line) in cubic feet per second from October 1, 2016 to September, 1 2017. Figure is from Grams and others (2018a).

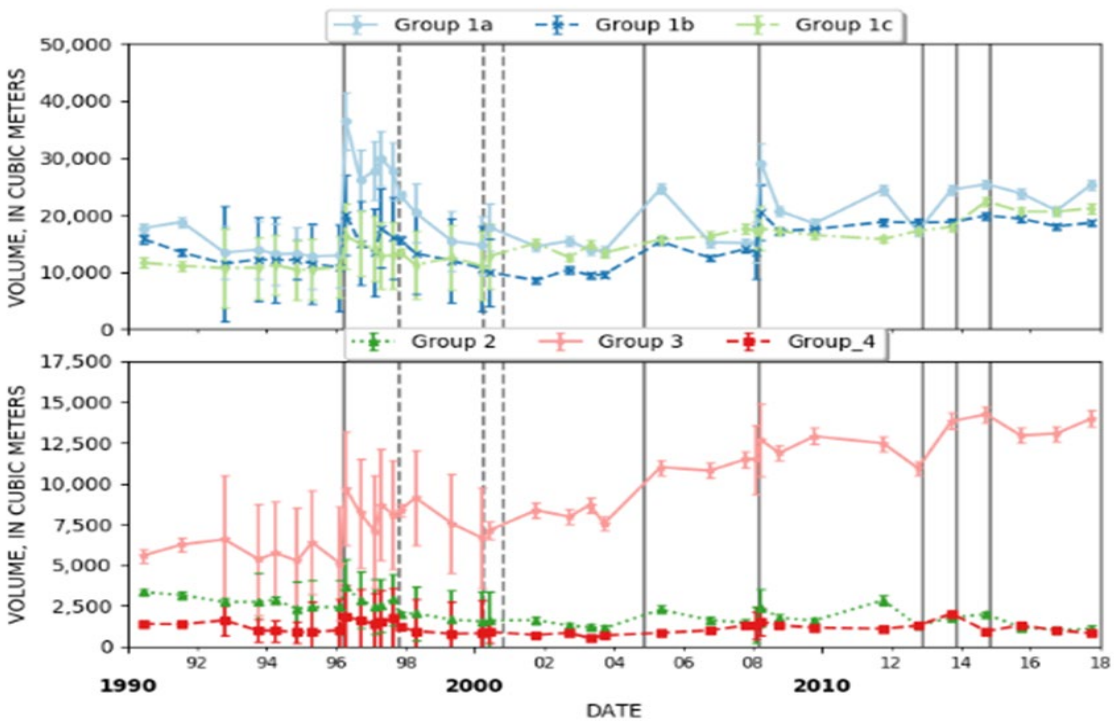

Figure 2. Sandbar volume (m^3) at long-term monitoring sites along the Colorado River in Grand Canyon National Park, Arizona by sandbar type from 1990 to 2018. Group 1a, 1b, and 1c are unvegetated, moderately vegetated and heavily vegetated reattachment bars, respectively (Mueller and others, 2018).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

REFERENCES

Buscombe, D., and Ritchie, A.C., 2018, Landscape classification with deep neural networks: Geosciences, v. 8, no. 7, article 244, https://doi.org/10.3390/geosciences8070244.

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.

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, online, https://doi.org/10.1002/rra.3349.

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.

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

PRODUCTS/REPORTS

Type	Title	Due Date	Date Delivered	Date Expected	Citations/Comments
USGS Data	Project B.1: Data from long-term sandbar monitoring sites	Annual	Jan 2018		To be presented at annual reporting meeting and www.gcmrc.gov/sandbar
USGS Data	Project B.2: Glen Canyon Channel Mapping Data		Jan 2018		To be presented at annual reporting meeting and https://grandcanyon.usgs.gov/portal/home/.
USGS Photos	Project B.1: Images from remote camera monitoring of sandbars	Annual	Jan 2018		Website: www.gcmrc.gov/sandbar
USGS Scientific Investigations Report	Project B.1 Report on causes of campsite area change	FY 2015	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.
USGS Open-File Report	Project B.1 Report on use of remote camera images for sandbar monitoring	FY 2017	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.
Conference Proceedings	Project B.2 Report on automated methods for substrate classification	FY 2018	Mar 2018		Buscombe, D., Grams, P.E., & Kaplinski, M., 2018, Probabilistic models of seafloor composition using multispectral acoustic backscatter: GeoHab 2018 International Symposium, R2Sonic Multispectral Backscatter competition entry. Download using online form at: https://www.r2sonic.com/geohab2018/.
USGS Data Release	Project B.1 Data on causes of campsite area change	FY 2015	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 Release	Project B.1 data on sand-area change	FY 2017	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 Release	Project B.2 Computer code automated methods for substrate classification	FY 2017	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.
USGS Data Release	Project B.1 data on sand-area change	FY 2017	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.
Journal article	Project B.1 Journal article on sand-area change	FY 2018	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, online, https://doi.org/10.1177/0309133318795846.
Journal article	Project B.1 Journal article on causes of campsite area change	FY 2017	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, online, https://doi.org/10.1002/rra.3349.
Journal article	Project B.2 Journal article on automated methods for substrate classification	FY 2018	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.2 Journal article on automated methods for image classification	FY 2018	Jun 2018		Buscombe, D., and Ritchie, A.C., 2018, Landscape classification with deep neural networks: Geosciences, v. 8, no. 7, article 244, https://doi.org/10.3390/geosciences8070244.
Journal article	Project B.2 Journal article on long-term monitoring of sand storage	FY 2018	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, online, https://doi.org/10.1002/esp.4489.
Journal article	Project B.1 Journal article on sandbar changes	FY 2017	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	FY 2017	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.

Project B Budget

Project B	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$438,312	$5,900	$34,500	$392,616	$0	$86,252	**$957,580**
Actual Spent	$393,329	$4,446	$44,881	$439,695	$0	$82,055	**$964,406**
(Over)/Under Budget	**$44,983**	**$1,454**	**($10,381)**	**($47,079)**	**$0**	**$4,197**	**($6,826)**
						FY18 Carryover	**($6,826)**

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

- Surplus salary due to an employee departing. This work was accomplished through cooperative agreements, resulting in greater than planned expenditures in that category.
- Increase in operating expenses was due to an unexpected equipment repair.

Project C: Riparian Vegetation Monitoring and Research

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC Brad Butterfield, NAU Emily Palmquist, USGS, GCMRC Laura Durning, NAU
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SUMMARY

Goals and Objectives FY 2018

Riparian vegetation is an important part of the 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 in 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 non-native 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 both rapid changes such as shifts in wetland communities, and slower changes such as tree growth and mortality, for example from 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).

Riparian vegetation monitoring data was collected between August 3 and October 12, 2018 and included sites between RM -15.5 and 240. Data were collected at a total of 99 randomly selected sites and 43 long-term monitoring sites (NAU sandbar monitoring sites) (Figure 1). This includes collecting data at RM -7.1 (Lunch Beach) in order to provide pre-Glen Canyon Dam LTEMP vegetation management treatment data for Glen Canyon National Recreation Area (GCNRA; see Element C.4). This site was selected by GCNRA for dead tamarisk removal and subsequent native vegetation reestablishment.

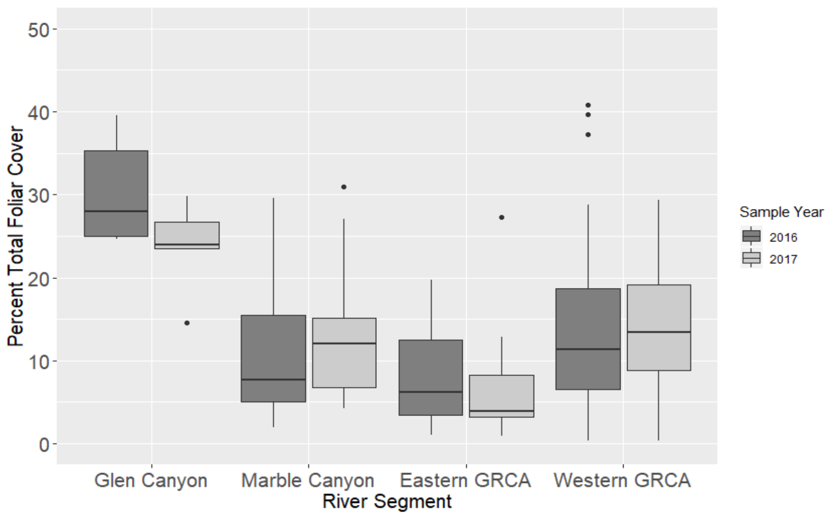

Figure 1. Estimates of percent total living foliar cover along the Colorado River downstream of Glen Canyon Dam summarized from riparian vegetation monitoring data collected in 2016 and 2017 (Butterfield and others, in prep).

An in-depth protocol describing riparian monitoring objectives and standard operating procedures was published in FY 2018 (Palmquist and others, 2018b). This peer-reviewed publication documents how data collection and management is conducted, to make our methods transparent and consistent over time. This document is available at https://doi.org/10.3133/tm2A14.

A database has been developed to manage all monitoring data collected from 2012 and into the future following the published monitoring protocol (Palmquist and others, 2018b). This database is currently being tested and modified for efficient data entry and management. Due to different sampling methods and data structure, historic (pre-2012) riparian vegetation data will not be housed in the new database. Digitization of those historic data (making them available for use) is ongoing as time and funding allow. Those data span 1991-2006 and consist of a variety of data types (e.g., some vegetation mapping, some marsh community data, some structure data), but not all types of data were collected across all time periods. All the original data sheets have been scanned and about 15% of the available historic data has been digitized. No further funding is budgeted for digitization of historic data and it is estimated that it would take approximately 60 weeks of work to complete.

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

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

In work completed prior to the FY 2018-2020 TWP, landscape-scale remote sensing of riparian vegetation was used successfully 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, 2017a; Sankey and others, 2015b; Ralston and others, 2008), and 3) mapped non-native invasive tamarisk vegetation impacted by the introduced tamarisk beetle using 2009 and 2013 imagery from Glen Canyon Dam to Lake Mead and 2013 airborne Light Detection and Ranging (LiDAR) (Sankey and others, 2016; Bedford and others, 2017). In 2018, 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; Durning and others, in press; Kasprak and others, 2018; Sankey and others, 2018).

In this project element, 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.*

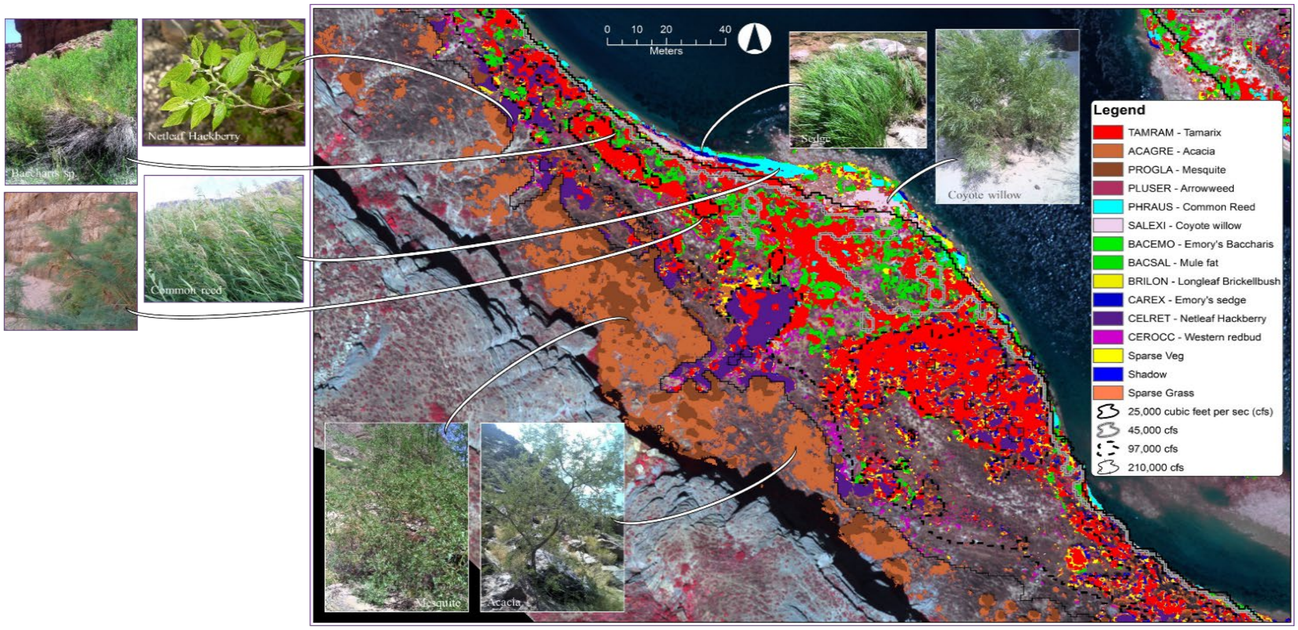

Figure 2. Example showing the Durning and others (in press) classification map of riparian vegetation by species based on the most recent overflight imagery acquired in 2013. The map extends from Glen Canyon Dam to Lake Mead and is the highest resolution and most current map of riparian vegetation for the Colorado River ecosystem.

With respect to objective C.2.1, in 2018 we finalized our map (Durning and others, in press; 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). We are in the process of publishing this as a USGS data release (Durning and others, in press).

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). We are analyzing the Durning and others (in press) and Sankey and others (2018) datasets to address the questions posed by objectives C.2.1 and C.2.2. We have identified three different planned outlets or deliverables for the results of these analyses.

First, 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” will be presented by Alan Kasprak in December 2018 which will cover 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 (Figure 3). Second, those preliminary results will be further developed into a peer-reviewed technical paper titled “The historic dynamics and future trajectory of sediment availability along the Colorado River in Grand Canyon: Results from field surveys and remote sensing” published in the proceedings of the Federal Interagency Sedimentation and

Hydrologic Modeling Conference convened in June 2019. Third, we have a manuscript in preparation that details our work on objectives C.2.1 and C.2.2 using the Durning and others (in press) and Sankey and others (2018) datasets to answer the following questions:

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

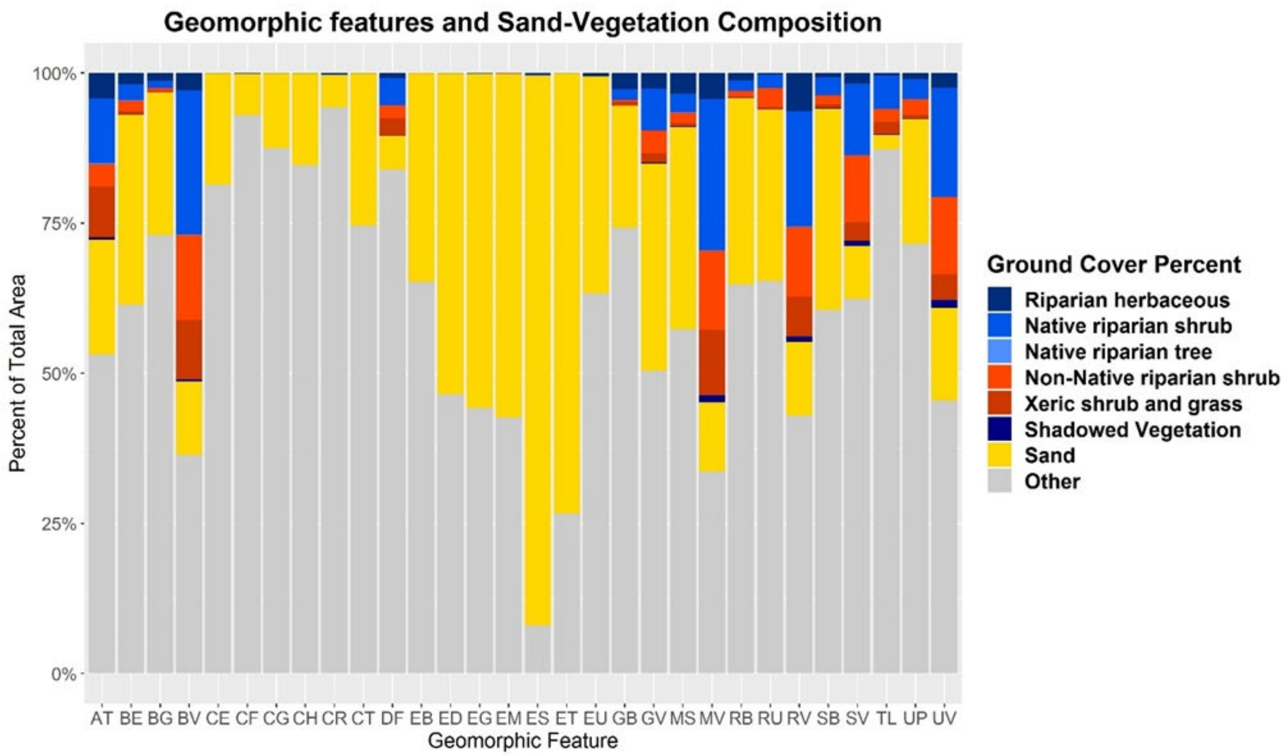

Figure 3. Example of preliminary results showing the percent area within each type of geomorphic feature covered by unvegetated, bare sand or associations of vegetation species mapped between Glen Canyon Dam and Lake Mead in the Durning and others (in press) and Sankey and others (2018) datasets, which are both based on the 2013 overflight imagery. The geomorphic feature codes are: AT (Alluvial terrace); BE (Undifferentiated eddy bar); BG (Undifferentiated eddy bar associated with gravel bar); BV (Densely vegetated undifferentiated eddy bar); CE (Channel adjacent eddy); CF (Channel adjacent debris fan); CG (Channel adjacent gravel bar w/o riffle); CH (Channel); CR (Channel in riffle/submerged debris fan); CT (Channel adjacent talus cone); DF (Debris fan); EB (Eddy downstream from bedrock constriction); ED (Eddy downstream from debris fan); EG (Eddy associated with gravel bar); EM (Channel-margin eddy); ES (Eddy downstream from geometric separation); ET (Eddy downstream from talus constriction); EU (Eddy upstream from debris fan or other constriction); GB (Gravel bar); GV (Densely vegetated gravel bar); MS (Channel-margin bar); MV (Densely vegetated channel-margin bar); RB (Reattachment bar); RU (Reattachment bar upstream from debris fan or other constriction); RV (Densely vegetated reattachment bar); SB (Separation bar); SV (Densely vegetated separation bar); TL (Talus cone); UP (Undifferentiated eddy bar upstream from debris fan or other constriction); UV (Densely vegetated undifferentiated eddy bar upstream from debris fan or other constriction).

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 2015-2017 workplan. In 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. The final deliverable associated with this work is planned for the last year of the FY 2018-2020 TWP, and thus we will provide more information about this work as it progresses in future annual reports.

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

Predictive models of riparian vegetation change in response to Glen Canyon Dam LTEMP flow scenarios can inform stakeholders about the potential influences of daily flows and alternative flows outlined in the LTEMP 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, as well as historic data) and flow data integrated with flow-response vegetation guilds to examine the influence of flow scenarios on species distributions and potential community change (Figure 4). The modeling done for LTEMP identified likely outcomes for plant community states, but at a basic level of presence or absence and expansion or contraction. This modeling provides more detail, potentially about specific species of interest to stakeholders, and will result in a better understanding of how dam operations change vegetation. We will test these predictions based on responses observed in long-term monitoring data to a wealth of hydrological and geomorphological factors (e.g., Figure 3). The results of this work will help inform the assessment of how ground-based sampling and data derived from the digital imagery can be most efficiently integrated (Elements C.1 and C.2) and will inform the implementation of experimental vegetation treatments (Element C.4).

As a step toward developing these models, Palmquist and others (2018a) quantitatively identified significant change in vegetation composition along the river with distance downstream. Three different vegetation communities are identified, which may respond differently to dam operations. These vegetation communities should be modeled separately or modeled in such a way that accounts for their different vegetation types. An extension of this work which aims to examine the influences of flow regime on these different communities has been started. Vegetation monitoring data, flow data, and environmental data are currently being compiled. The results of this study will be presented later in the FY 2018-2020 TWP timeframe.

Vegetation can significantly impact sand resources, specifically surface sand area available for recreation and camping. Thus, a more detailed understanding of vegetation responses to flow regimes on sandbars, and associated impacts on sandbar elevation and exposed sand, is warranted. Repeat vegetation surveys have been conducted on 43 NAU sandbars, during the period of September 26 – October 12, 2018. The data from similar surveys conducted from 2013-2016 were used in conjunction with the high resolution digital elevation models of the sandbars and interpolated climate data to develop ecological niche models, or habitat suitability models, of the 16 most abundant woody plant species and 58 most abundant herbaceous plant species. These models were used to estimate optimal conditions of annual inundation duration and elevation above base flows within sandbars, as well as climatic conditions along the river corridor, for each of the modeled species. These niche optimum estimates were coupled with community composition data to determine; 1) how closely and predictably vegetation communities track hydrological and climatic variation, and 2) how hydrological and climatic variation interact to shape vegetation composition. Both woody and herbaceous vegetation tracked variation in elevation above base flow more closely than inundation duration, suggesting that depth to soil moisture may generally play a stronger role in structuring vegetation than inundation does.

Vegetation also tracked variation in temperature, particularly minimum temperature, more closely than annual precipitation. Interestingly, inundation duration interacted significantly with temperature to shape vegetation composition, selecting against inundation-tolerant species in hot environments or heat-tolerant species in water-logged conditions. We hope to test the causality of this relationship through greenhouse experiments and physiological monitoring in the future. These findings have important implications for the nature and sustainability of vegetation treatments, as well as understanding the interactive effects of flow regime and climate on vegetation composition.

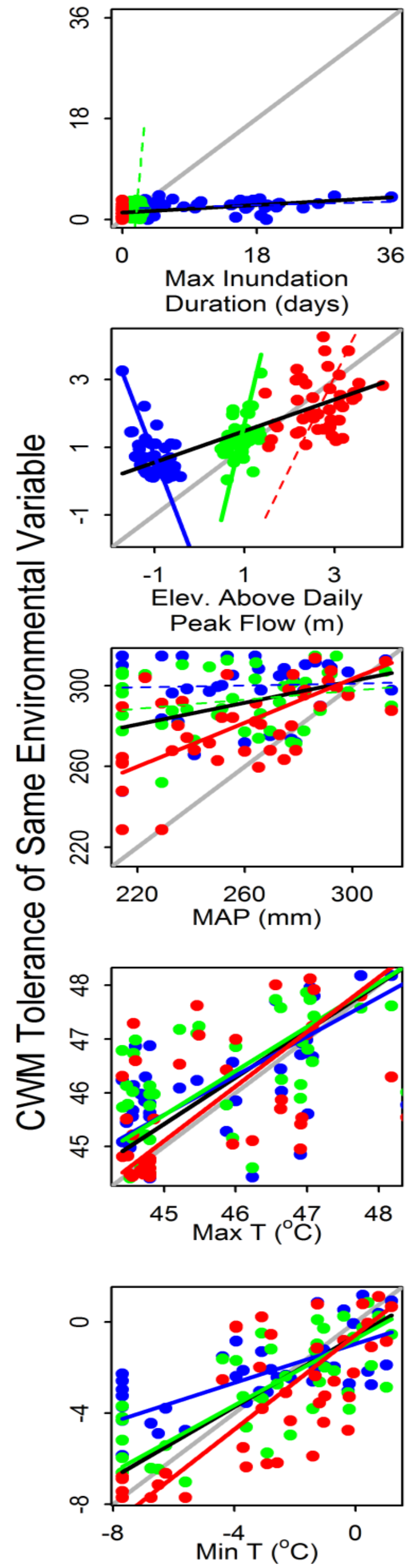

Figure 4. Woody vegetation tracking of hydrology and climate in the active channel (blue), active floodplain (green) and inactive floodplain (red). Values are the community-weighted mean (CWM) tolerance of each of the environmental variables. From Butterfield and others, 2018.

These results will be presented at the 2019 Annual Reporting Meeting as they relate to HFEs. These results have also been published by Butterfield and others (2018). These niche models form the foundation of future products, including; 1) modeling of vegetation-sand feedbacks, 2) process-based vegetation models, and 3) decision support tools for vegetation treatments. Models will be updated annually as new data are collected and assimilated.

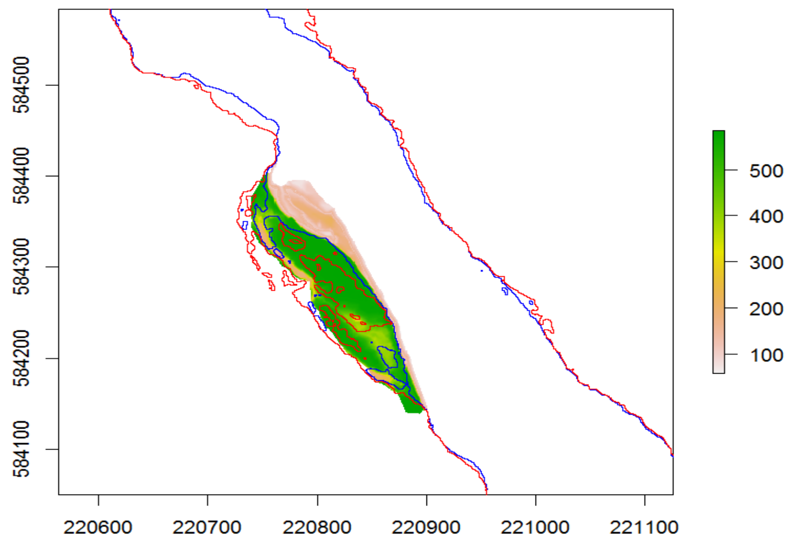

Figure 5. Predicted suitable habitat for tamarisk at Kwagunt Marsh in 2016. Higher values indicate greater suitability. Blue and red lines demarcate 25,000 and 45,000 ft^3/s modeled flow lines.

Project Element C.4. Vegetation Management Decision Support

GCMRC is partners with the National Park Service (NPS) and Native American Tribes on the Riparian Vegetation Mitigation Project C.7 Experimental Vegetation Treatment as described in the LTEMP ROD (U.S. Department of the Interior, 2016). 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 2018, GCMRC scientists, under the requirements of element C.4, have hosted and helped organize and lead two in-person meetings and one web-based meeting among all the project partners. GCMRC scientists have specifically helped develop and contribute to lists of pilot sites and vegetation species for vegetation management treatments in GCNRA and Grand Canyon National Park. Work completed collectively by all project partners in 2018 will provide the framework for implementation of pilot experimental vegetation management treatments by the NPS that will begin in spring of 2019.

In cooperation with the NPS, GCMRC scientists are working on an assessment of genetic structure and differentiation of cottonwood (*Populus fremontii*), Goodding's willow (*Salix gooddingii*), and coyote willow (*Salix exigua*) (laboratory work funded by Grand Canyon National Park). Preliminary analyses suggest that cottonwoods in Grand Canyon are clearly genetically distinct from cottonwoods outside of Grand Canyon and the genetic structure of cottonwoods also show differences among geographic regions within Grand Canyon. These results are expected to inform the development of planting materials for the LTEMP project vegetation management treatments.

A white paper developed in conjunction with stakeholders describing vegetation treatment objectives, approaches and monitoring protocols was originally planned as a deliverable in 2018. However, project partners decided that in lieu of a new white paper, there was sufficient basis for moving forward with the project by developing site lists, species lists, and a document describing the project, project partners, roles, responsibilities, and data handling. GCMRC scientists have helped develop each of these.

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, USA: 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., 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, online, 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., 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.

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.

Durning, L.E., Sankey, J.B., Chain, G.R., and Sankey, T.T., 2017a, 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., Chain, G.R., and Sankey, T.T., 2017b, 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., Bedford, A., and Sankey, J.B., *in press*, Riparian species vegetation classification for Colorado River with Grand Canyon—Derived from 2013 airborne image collection: U.S. Geological Survey data release.

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, online, 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

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., http://pubs.usgs.gov/of/2008/1216/.

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, http://dx.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.

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.

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

PRODUCTS/REPORTS

Type	Title	Due Date	Date Delivered	Date Expected	Citation/Comments
Journal	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.
Dataset	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.
Journal	Hydrological regime and climate interactively shape riparian vegetation composition along the Colorado River, Grand Canyon		Jun 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, online, https://doi.org/10.1111/avsc.12390.
Dataset	Climate, hydrology and riparian		July 2018		Palmquist, E.C., 2018, Climate, hydrology and riparian vegetation composition data, Grand Canyon, Arizona: U.S. Geological Survey data

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citation/Comments**
	vegetation composition data, Grand Canyon, Arizona				release, https://doi.org/10.5066/F7DN4493.
Poster 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.
Techniques and Methods	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.
Journal	A comparison of riparian vegetation sampling methods along a large, regulated river.			March 2019	Palmquist, E.C., Sterner, S.A., and Ralston, B.E., *in review*, A comparison of riparian vegetation sampling methods along a large, regulated river: submitted to River Research and Applications.
Journal	Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA.		Jan 2018		[Final deliverable for Project 4 of 2015-2017 workplan. Work was completed on time for presentation at the Winter 2018 Annual Reporting Meeting. Because the meeting was rescheduled due to the Federal Government Shutdown, project staff were not able to present. Project staff plan to present this work at the Winter 2019 ARM and HFE workshop.] 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,

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citation/Comments**
					https://doi.org/10.1016/j.ecolind.2018.02.026.
Dataset	Sand classifications along the Colorado River in Grand Canyon derived from 2002, 2009, and 2013 high-resolution multispectral airborne imagery		Sept 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.
Dataset	Riparian species vegetation classification for Colorado River with Grand Canyon: Derived from 2013 airborne image collection			Dec 2018	Durning, L.E., Sankey, J.B., Bedford, A., and Sankey, J.B., *in press*, Riparian species vegetation classification for Colorado River with Grand Canyon—Derived from 2013 airborne image collection: U.S. Geological Survey data release.
Conference Proceedings Peer-reviewed Technical Paper	The historic dynamics and future trajectory of sediment availability along the Colorado River in Grand Canyon: Results from field surveys and remote sensing			June 2019	Kasprak and others, *in prep.,* The historic dynamics and future trajectory of sediment availability along the Colorado River in Grand Canyon—Results from field surveys and remote sensing: Improving Resiliency and Sustainability of Watershed Resources and Infrastructure, Reno, Nev., June 24-28, 2018, Proceedings of the 2019 Federal Interagency Sedimentation and Hydrologic Modeling Conference.
Conference 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 and others, 2018, Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the Colorado River in Grand Canyon: American Geophysical Union Fall Meeting, Washington, D.C., Dec. 10-14, 2018.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citation/Comments**
Presentation	Riparian remote sensing in Glen and Grand Canyons: Vegetation, sediment, and cultural resources		Nov 2017		Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Riparian remote sensing in Glen and Grand Canyons—Vegetation, sediment, and cultural resources—presentation: Colorado River Steering Committee, Face to Face Meeting, Lower Colorado Region Regional Training Center, Boulder City, Nev., November 15th, 2017.
Presentation	Relating riparian vegetation, the Colorado River, climate, and resource management via remote sensing in Grand Canyon		Nov 2017		Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Relating riparian vegetation, the Colorado River, climate, and resource management via remote sensing in Grand Canyon: Northern Arizona University, Biology Department Seminar, Flagstaff, November 6th, 2017.

Project C Budget

Project C	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$270,817	$7,285	$4,000	$178,210	$0	$49,233	**$509,545**
Actual Spent	$264,896	$693	$1,777	$184,116	$0	$47,118	**$498,600**
(Over)/Under Budget	**$5,921**	**$6,593**	**$2,223**	**($5,906)**	**$0**	**$2,115**	**$10,945**
						FY18 Carryover	**$10,945**

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

- Surplus salary due to a technician being hired later than planned
- Surplus in travel was due to employees not being able to attend a conference they had planned on attending.
- Original labor estimate was too low for labor to cooperator, so the amount was increased.

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

Project Lead	Joel Sankey	**Principal Investigator(s)** (PI)	Joel Sankey, USGS, GCMRC Helen Fairley, USGS, GCMRC
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SUMMARY

Glen Canyon Dam 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% below 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, the 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 the 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 tied to regulated flow regimes (U.S. Department of the Interior, 2016a; East and others, 2016).

The LTEMP EIS predicts that conditions for achieving the goal of preservation of cultural resources, termed "preservation in place," will be enhanced as a result of implementing the selected alternative. 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 GCNRA (East and others, 2016; U.S. Department of the 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 regular 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 through 2036, as specified under the LTEMP (U.S. Department of the Interior, 2016b). The data and analyses from this project will allow the GCDAMP to objectively evaluate whether and how these non-flow and flow actions 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 CRe.

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 2018 are described below for each project element.

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

Summary of work completed in 2018

- A field trip was conducted in May of 2018. Eight archaeological sites were surveyed with LiDAR per the protocol described in the GCMRC plan for monitoring effects of geomorphic processes at archaeological sites in Grand and Glen Canyon (shared with stakeholders as a draft plan in 2016 during the FY 2015-2017 TWP, and again more recently with signatories of the Programmatic Agreement for Cultural Resources as part of the Historic Preservation Plan).
- Weather data were collected at six stations, one at Ferry Swale in Glen Canyon, one at Lees Ferry, and one at each of four Marble and Grand Canyon archaeological sites (e.g., Caster and others, 2014, 2018; Sankey and others, 2018a,b). Stations collected measurements of rainfall, wind speed and direction, temperature, barometric pressure, and relative humidity at 4-minute timesteps.
- At three sites, stationary cameras took photographs up to four times per day to record information about the timing and nature of landscape change.
- Monitoring data described above were processed and archived at GCMRC. A report summarizing archaeological site monitoring data acquired from 2010-2018 has been drafted by project staff and is in review and revision at GCMRC. The draft 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."
    - This report and the monitoring data contained therein will provide the baseline for evaluation of pilot experimental vegetation management treatments that will be implemented by NPS beginning in 2019 per the LTEMP EIS (U.S. Department of the Interior, 2016a) to improve the condition of archaeological sites, including sand resources.
    - These monitoring data were also 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 are conducted consistently in consecutive years (Sankey and others, 2018b). Figure 1 shows the changes in total sediment storage associated with each HFE at the four dunefields studied by Sankey and others (2018b). Figure 1 also shows the changes in total sediment storage specifically

at the archaeological site located within each respective dunefield. Figure 2 summarizes the results in Figure 1 and shows that proportion of the four archaeological sites with a positive sediment budget has increased over the time frame spanning the 2012, 2013, 2014, and 2016 HFEs. A positive sediment budget indicates that an archaeological site area has gained (e.g., been buried) in sediment, which is a mechanism for achieving the LTEMP goal for cultural resources of “preservation in place.”

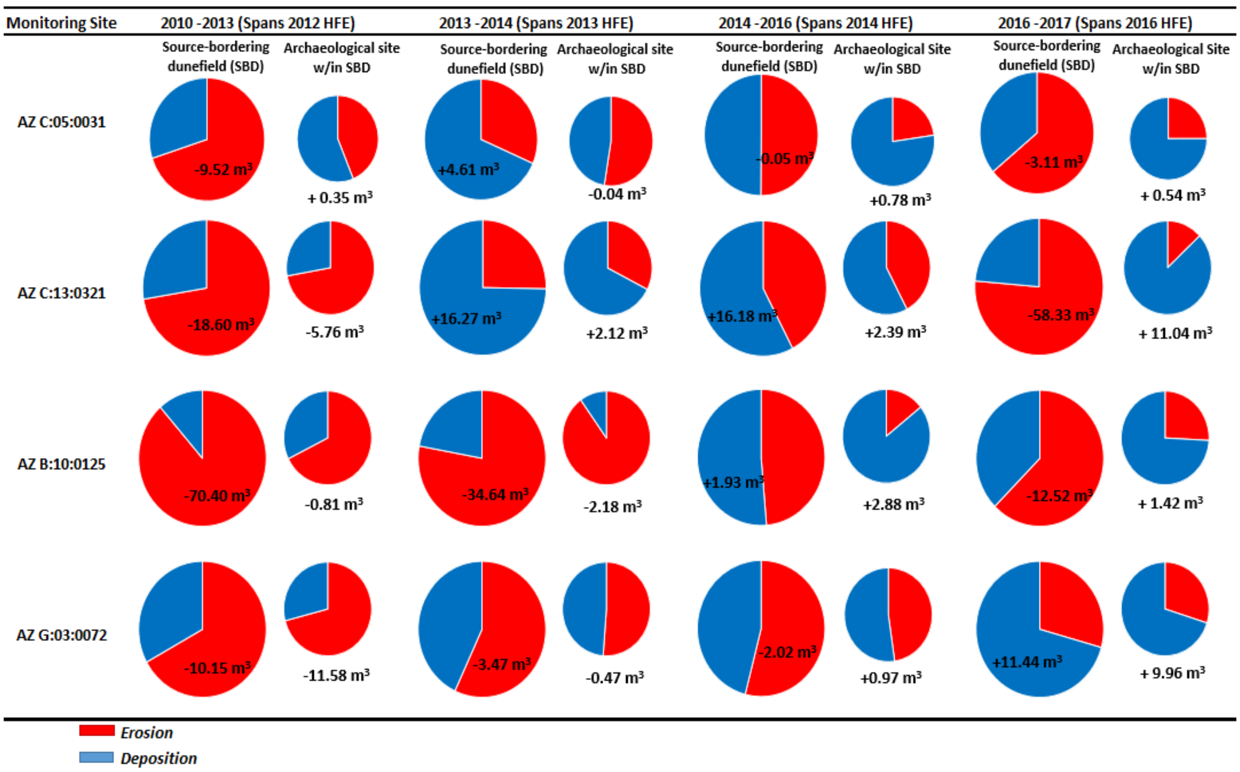

Figure 1. Results from long-term monitoring of changes in sediment storage at four archaeological sites that are located within source-bordering aeolian dunefields which are downwind of river sandbars resupplied with sand during HFEs. Pie charts depict the relative proportion of erosion and deposition by sediment volume. Values in units of m^3 below each pie chart indicate the net change in sediment storage due to erosion and deposition. Positive net changes indicate a positive sediment budget. For archaeological sites, a positive sediment budget indicates the site area has gained (e.g., been buried) in sediment, which is a mechanism for achieving the LTEMP goal for cultural resources of “preservation in place.”

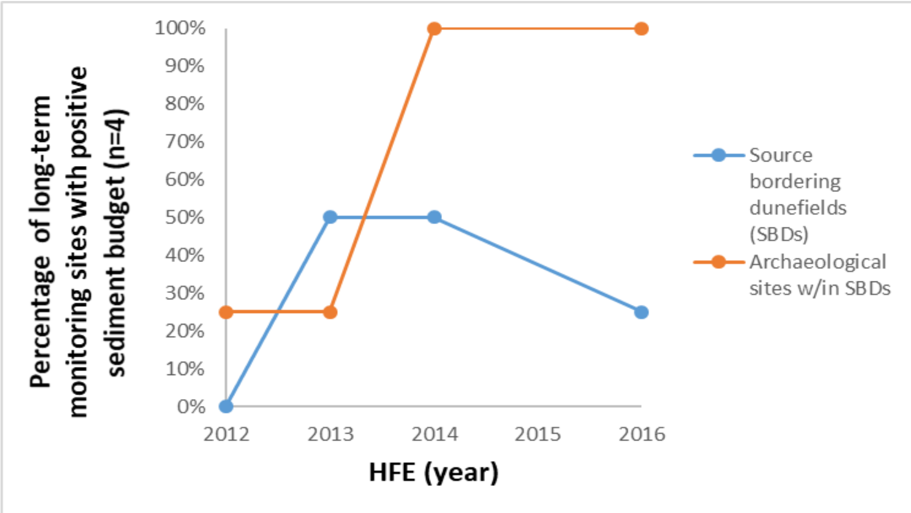

Figure 2. Summary of results presented in Figure 1. The proportion of the four long-term monitoring archaeological sites with a positive sediment budget has increased over the time frame spanning the 2012, 2013, 2014, and 2016 HFEs. A positive sediment budget indicates that an archaeological site area has gained (e.g., been buried) in sediment, which is a mechanism for achieving the LTEMP goal for cultural resources of "preservation in place."

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

In FY 2018, Fairley prepared a detailed report summarizing and synthesizing past research, monitoring, and mitigation activities funded by Reclamation for cultural resources located along the Colorado River in lower Glen, Marble, and Grand Canyons. The report is titled "Dam regulated flows and impacts to cultural resources downstream of Glen Canyon Dam: A synthesis of learning from three decades of research, monitoring and mitigation activities." This synthesis was undertaken to help inform development of a new Historic Preservation Plan for historic properties in the CRe and to aid future decision-making and management of cultural sites affected by dam operations.

The project involved assembling, reviewing, evaluating and synthesizing all past monitoring, research, and mitigation projects and associated data collected by NPS archaeologists, tribal cooperators, GCMRC cooperators, and USGS scientists related to cultural resources within the Area of Potential Effect (U.S. Department of the Interior, 1995) from dam operations over the past three decades (late 1980s through 2017). In addition to a lengthy narrative and bibliography, the synthesis includes a two-part management summary table for all identified historic properties within the Area of Potential Effect from dam operations for which publicly accessible information is available. For each historic property, the table includes a summary of prior condition assessments, vulnerability assessments, and previous actions (monitoring, research, and mitigation activities) undertaken at each property, along with prior treatment recommendations derived from the Damp and others (2007) treatment plan, where applicable. The assistance of NPS staff and the Hopi Tribe in tracking down copies of various obscure unpublished reports was instrumental in ensuring that the synthesis was comprehensive, and their help is gratefully acknowledged. An initial draft report was provided to Reclamation in early July 2018, and a second draft was provided to signatories of the new Programmatic Agreement for Cultural Resources for their review and comment in early September 2018. A final version of the synthesis is expected to be published as a USGS Open-File Report in 2019.

REFERENCES

Caster, J., Dealy, T., Andrews, T, Fairley, H., Draut, A., and Sankey, J., 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://dx.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.

Damp, J., Pederson, J., and O'Brien, G., 2007, Geoarchaeological investigations and archaeological treatment plan for 151 sites in the Grand Canyon, Arizona: Salt Lake City, Utah, unpublished report prepared for Bureau of Reclamation, Upper Colorado River Region, 502 p.

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, http://dx.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., http://dx.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, online, https://doi.org/10.1177/0309133318795846.

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, http://dx.doi.org/10.1002/2015JG002991.

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

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, http://dx.doi.org/10.1029/1999WR900285.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam, Colorado River storage project, Arizona—Final Environmental Impact Statement: Salt Lake City, Utah, U.S. Department of the Interior, Bureau of Reclamation, 337 p. plus appendices, http://www.usbr.gov/uc/envdocs/eis/gc/gcdOpsFEIS.html.

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

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

PRODUCTS/REPORTS

Type	Title/Citation	Due Date	Date Delivered	Date Expected	Comments
Journal article	Sankey, J.B., Kasprak, A., Caster, J.J., East, A.E., and Fairley, H., 2018, The response of source-bordering aeolian dunefields to sediment-supply changes 1—Effects of wind variability and river-valley morphodynamics: Aeolian Research, v. 32, p. 228-245, https://doi.org/10.1016/j.aeolia.2018.02.005.	FY 2018	FY 2018		Final deliverable for Project 4 of 2015-2017 workplan. Work was completed on time for presentation at the Winter 2018 Annual Reporting Meeting. Because the meeting was rescheduled due to the Federal Government Shutdown, project staff were not able to present. Project staff plan to present this work at the Winter 2019 ARM and HFE workshop.

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Type	**Title/Citation**	**Due Date**	**Date Delivered**	**Date Expected**	**Comments**
Journal article	Sankey, J.B., Caster, J.J., Kasprak, A., and East, A.E., 2018, The response of source-bordering aeolian dunefields to sediment-supply changes 2—Controlled floods of the Colorado River in Grand Canyon, Arizona, USA: Aeolian Research, v. 32, p. 154-169, https://doi.org/10.1016/j.aeolia.2018.02.004.	FY 2018	FY 2018		Final deliverable for Project 4 of 2015-2017 workplan. Work was completed on time for presentation at the Winter 2018 Annual Reporting Meeting. Because the meeting was rescheduled due to the Federal Government Shutdown, project staff were not able to present. Project staff plan to present this work at the Winter 2019 ARM and HFE workshop.
Journal article	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, online, https://doi.org/10.1177/0309133318795846.	FY 2018	FY 2018		Final deliverable for Project 4 of 2015-2017 workplan. Work was completed on time for presentation at the Winter 2018 Annual Reporting Meeting. Because the meeting was rescheduled due to the Federal Government Shutdown, project staff were not able to present. Project staff plan to present this work at the Winter 2019 ARM and HFE workshop.
USGS Dataset	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.	FY 2018	FY 2018		New data is published every other year associated with this initial report (there is an additional approximately 1-year lag due to the USGS publications process): Caster, J., Dealy, T., Andrews, T, Fairley, H., Draut, A., Sankey, J., and Bedford, D., 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., http://dx.doi.org/10.3133/ofr20141247.
Conference Presentation	Relating riparian vegetation, the Colorado River, climate, and resource management via remote sensing in Grand Canyon, at Northern Arizona	FY 2018	FY 2018		Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Relating riparian vegetation, the

PRODUCTS/REPORTS					
Type	**Title/Citation**	**Due Date**	**Date Delivered**	**Date Expected**	**Comments**
	University, Biology Department Seminar, Flagstaff, November 6th, 2017.				Colorado River, climate, and resource management via remote sensing in Grand Canyon—presentation: Northern Arizona University, Biology Department Seminar, Flagstaff, November 6th, 2017.
Conference Presentation	Riparian remote sensing in Glen and Grand Canyons: Vegetation, sediment, and cultural resources, at Colorado River Steering Committee, Face to Face Meeting, Lower Colorado Region Regional Training Center, Boulder City, Nev., November 15th, 2017.	FY 2018	FY 2018		Sankey, J.B., Sankey, T.T., Durning, L., Kasprak, A., Bedford, A., Ralston, B., Palmquist, E., Grams, P., Buscombe, D., Schmidt, J., 2017, Riparian remote sensing in Glen and Grand Canyons—Vegetation, sediment, and cultural resources: Colorado River Steering Committee, Face to Face Meeting, Lower Colorado Region Regional Training Center, Boulder City, Nev, November 15th, 2017.
Conference Presentation	Inferring the effects of sediment supply changes on sediment connectivity from river-valley morphodynamics, presented at 2017 Fall Meeting, AGU, New Orleans, LA, December 11-15, 2017.	FY 2018	FY 2018		Sankey, J.B., Kasprak, A., Caster, J., and East, A.E., 2017, Inferring the effects of sediment supply changes on sediment connectivity from river-valley morphodynamics: 2017 AGU Fall Meeting, New Orleans, LA, December 11-15, 2017, Abstract EP31A-0330, https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/242852.
Conference Presentation	The effect of topographic survey technique and resolution on the interpretation of geomorphic change in river valleys. Presented at 2017 Fall Meeting, AGU, New Orleans, LA, December 11-15, 2017.	FY 2018	FY 2018		Kasprak, A., Bransky, N., Caster, J., Sankey, J.B., and Sankey, T.T., 2017, The effect of topographic survey technique and resolution on the interpretation of geomorphic change in river valleys, in 2017 AGU Fall Meeting, New Orleans, LA, December 11-15, 2017, Abstract EP31D-0379, https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/221737.
Conference Presentation	Flow alteration, river valley morphology, and the influence of Glen Canyon Dam on sediment availability along the	FY 2018	FY 2018		Kasprak, A., Sankey, J.B., Buscombe, D., Durning, L., Caster, J., Grams, P., East, A., Butterfield, B., 2018, Flow alteration, river valley morphology, and the influence of Glen Canyon

PRODUCTS/REPORTS					
Type	**Title/Citation**	**Due Date**	**Date Delivered**	**Date Expect ed**	**Comments**
	Colorado River in Grand Canyon. Presented at 2018 Fall AGU Meeting, Washington, D.C., December 1-14, 2018.				Dam on sediment availability along the Colorado River in Grand Canyon—presentation: 2018 Fall AGU Meeting, Washington, D.C., December 1-14, 2018, Abstract EP33B-04, https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/394299.
Conference Presentation	Beyond compliance—Evolution and design of a program to monitor downstream dam effects at archaeological sites in Glen and Grand Canyons, Arizona. Presented at 2018 Pecos Conference of Southwestern Archaeology, Flagstaff, Ariz., August 8-12, 2018.	FY 2018	FY 2018		Fairley, H., Sankey, J., East, A., Caster, J., and Kasprak, A., 2018, Beyond compliance—Evolution and design of a program to monitor downstream dam effects at archaeological sites in Glen and Grand Canyons, Arizona—presentation: 2018 Pecos Conference of Southwestern Archaeology, Flagstaff, Ariz., August 8-12, 2018.
Report	Dam regulated flows and impacts to cultural resources downstream of Glen Canyon Dam: A synthesis of learning from three decades of research, monitoring and mitigation activities	FY 2019		2019	Fairley, H., *in review*, Dam regulated flows and impacts to cultural resources downstream of Glen Canyon Dam—A synthesis of learning from three decades of research, monitoring and mitigation activities: U.S. Geological Survey Open-File Report.

Project D Budget

Project D	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$186,361	$7,250	$11,075	$0	$0	$31,843	**$236,529**
Actual Spent	$165,884	$5,371	$19,490	$0	$0	$29,674	**$220,419**
(Over)/Under Budget	**$20,477**	**$1,879**	**($8,415)**	**$0**	**$0**	**$2,169**	**$16,110**
						FY18 Carryover	**$16,110**

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

- Surplus salary due to an employee's appointment ending, and the rehire process taking longer than anticipated.
- Operating expenses were higher than estimated due to some required maintenance on remote sensing equipment.

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
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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 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 external funding from Reclamation (see Appendix 1).

During FY 2018, we improved the water temperature model currently used to make predictions in the CRe and began to elucidate spatio-temporal patterns in nutrients throughout the CRe. While long-term nutrient monitoring at Lees Ferry (RM 0) shows a strong correspondence between nutrient availability in the reservoir outflow and in the Lees Ferry reach (Vernieu, 2009), there are very few measurements of nutrients downstream of the Paria River inflow, with no measurements of soluble reactive phosphorous (SRP) routinely made. During FY 2018, we began measuring tributary inputs of nutrients, completed diurnal studies of nutrient concentrations at both Lees Ferry and Diamond Creek (RM 225), and conducted a longitudinal survey of key nutrients. Key findings were that there was substantial diurnal variation in nutrients but limited longitudinal variation and that the Paria River may contribute substantial inputs of phosphorous.

During FY 2018, we made substantial 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. We also began development of semi-automated techniques for classifying submersed aquatic vegetation in the Glen Canyon reach from imagery, providing a means for future monitoring of change in vegetation. Progress in linking temperature and nutrients to higher trophic levels was slower. Attempts to install artificial streams at Lees Ferry have met with logistical constraints that appear insurmountable and we are currently considering experiments that can be conducted under more controlled settings to address questions put forth in the work plan. During the first half of FY 2018, we invested considerable unanticipated time into development of a brown trout model in response to the stakeholder motion approved by the AMWG to conduct a brown trout workshop and as a result did not make as much progress on developing an ecosystem model as hoped. Provided there are no similar unanticipated modelling requests of a similar magnitude in FY 2019, we expect more progress.

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 LTEMP EIS. Temperature predictions were generated using a linear warming model, but this model overestimates Colorado River temperatures by ~2°C in western Grand Canyon (Figure E.1.1a). 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 E.1.1a). We are using this model to explore how changes in air temperature, discharge, and release temperatures may change water temperatures throughout the CRe.

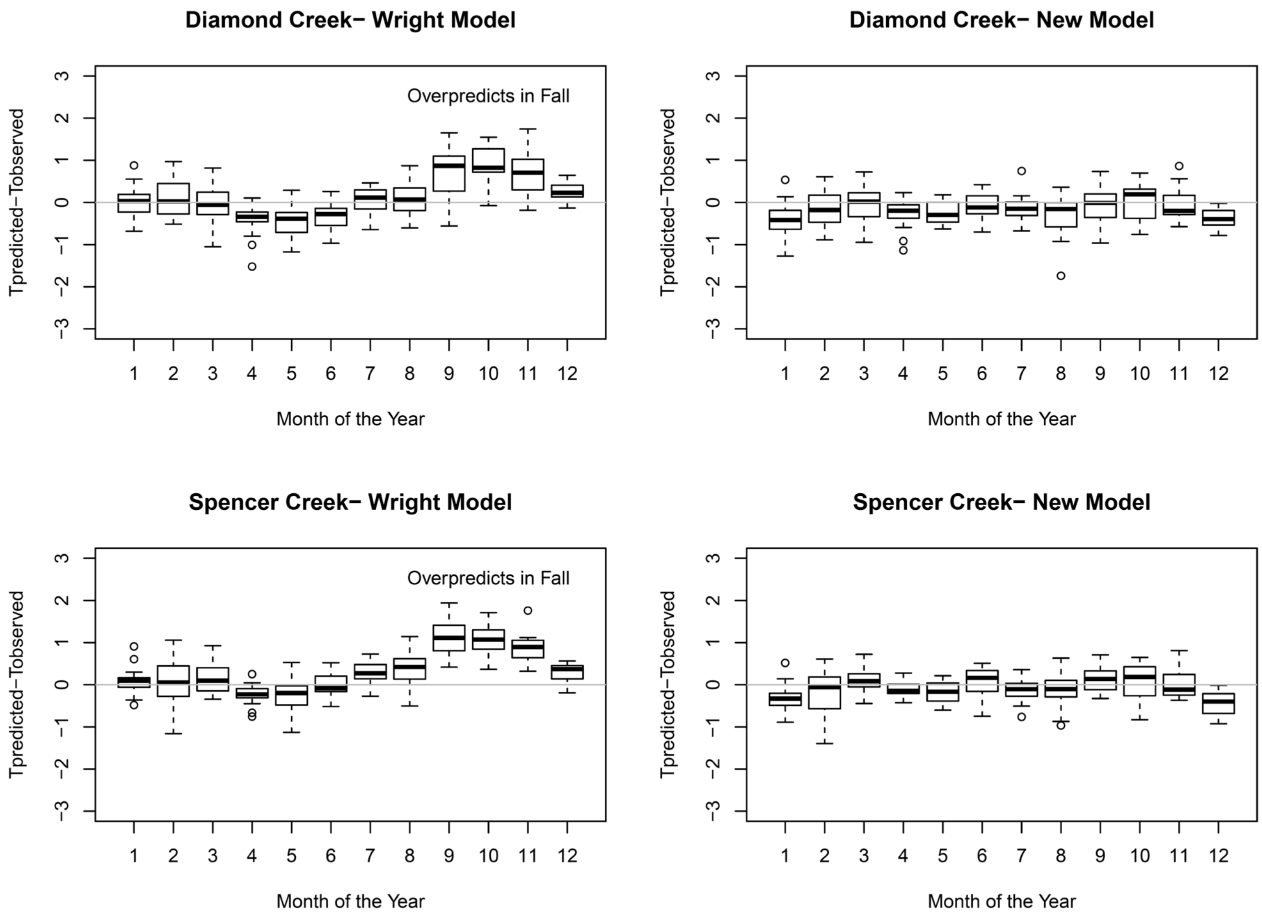

Figure E.1.1a. Comparison of residuals from the current model used for modeling water temperature in Grand Canyon (linear, Wright and others, 2009) relative to the new model we developed that includes an exponential decay in warming combined with the use of other data sources including solar radiation. 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).

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.

Distinct diel (day-night) patterns in river nutrient availability can occur due to patterns in direct uptake by photosynthesizers as well as associated changes in abiotic conditions such as pH

(Harrison and others, 2005; Cohen and others, 2013). We conducted spring diel sampling at both Lees Ferry and Diamond Creek to assess the degree to which nutrient availability varied over a 24-hour cycle. We found more variation in dissolved, biologically available phosphorus across a 24-hour period at each of these stations than was recorded for spring longitudinal sampling of the entire river corridor from Lees Ferry to Pearce Ferry (conducted at 7:00 am each morning). SRP ranged from undetectable (< 0.001 mg/L) to 0.003 mg/L across a 24-hour period at Lees Ferry and from undetectable to 0.004 mg/L at Diamond Creek. In contrast, SRP was undetectable for all longitudinal samples collected (only collected during the morning). Thus, any efforts to discern patterns in riverine nutrient availability should standardize for time-of-day.

Magnitude of reservoir releases can affect the “cone of influence” or the region of the Lake Powell water column from which water is withdrawn (Bureau of Reclamation, 2011). Because phosphorus concentrations vary by depth, we hypothesized that the experimental bug flows implemented during the spring and summer of FY 2018 may affect water column phosphorus concentrations. Total phosphorus, total dissolved phosphorus, and SRP were sampled at Lees Ferry at 10:30 am during three weekdays and three weekends in the month of August. No differences were found in total phosphorus or total dissolved phosphorus (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).

While Glen Canyon Dam outflow dominates the water budget in the Colorado River, the role of tributaries as significant nutrient sources to the river is not well known. We conducted grab sampling of nine tributaries thought to be potentially important nutrient sources during the spring of 2017. Most of the tributaries were sampled at base flow, however, Shinumo and Tapeats Creeks had elevated flows when sampling occurred. The highest total phosphorus concentrations came from the Paria River (0.1 mg/L), whereas the highest SRP concentrations came from Tapeats Creek (0.073 mg/L). Grab samples do not indicate that any of the tributary inflows could be significant enough to influence the phosphorus budget of the mainstem Colorado River, at least at baseflow.

Storms can be responsible for large fractions of total riverine phosphorus loads, and phosphorus-discharge hysteresis can vary substantially (Bowes and others, 2005). The Paria River had the highest total phosphorus concentrations of any tributary tested during both spring 2017 sampling described above 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. We sampled the Paria River during a 5-hour 700 ft^3/s storm and recorded concentrations of total phosphorus upwards of 5 mg/L. There was no apparent relationship between phosphorus concentrations and discharge across the 500-860 ft^3/s range that we sampled. Given these results, this relatively small storm is estimated to contribute somewhere around 15% of the monthly total phosphorus loaded to the Colorado River. If we assume similar total phosphorus concentrations for the larger storm that occurred a few days later than 50% of the August total phosphorus loading and 8% of the annual loading could be due to storm inputs. These findings support the installation of a refrigerated ISCO sampler for automated storm sample collection, as was proposed and budgeted in the FY 2018-2020 TWP. This work is currently planned for winter FY 2019. 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 2018, we developed a working method for detecting alkaline phosphatase, an indicator of phosphorus limitation, in Colorado River samples. We found varying levels of alkaline phosphatase in longitudinal sampling of the Colorado, suggesting that phosphorus limitation is variable depending on river reach. We plan 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 together with major water column phosphorus forms.

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, measured as GPP. GPP 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. Previously, data from one site, Diamond Creek, was analyzed using semi-mechanistic models to determine drivers of GPP (Hall and others, 2015). Initial modeling results from the six long term monitoring sites in Grand Canyon reveal variable season patterns in GPP (Figure E.2.1a). The magnitude of production predicted by these models is highly dependent on our ability to estimate gas transfer, and we are working to improve our estimates of gas transfer, so the magnitudes of production presented here are preliminary. Nonetheless, seasonal patterns in peak production are not sensitive to errors in the modeling of gas transfer, suggesting that the timing of peak GPP varies longitudinally throughout the river. 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. Analysis of this data is planned for winter-spring of FY 2019.

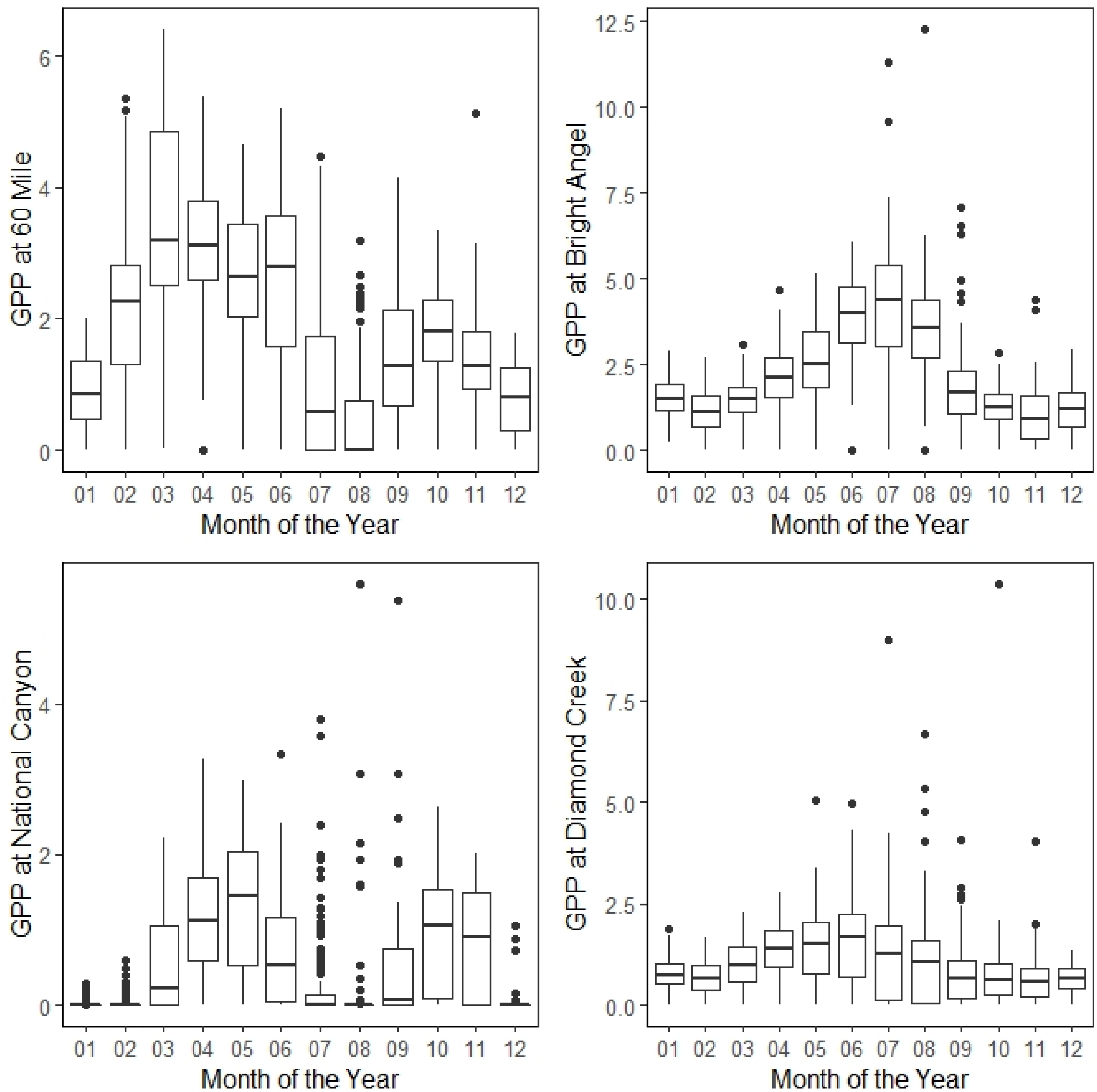

Figure E.2.1a. Monthly modeled gross primary production (GPP) rates across at four sites with long term dissolved oxygen data in the Colorado River. Daily GPP estimates displayed here are from May 2011 through October 2016, although time frames vary slightly by site (60 Mile, n=1453; Bright Angel Creek RM 88, n=1733; National Canyon RM 167, n=1267; and Diamond Creek RM 225, n=1887).

Understanding the environmental drivers of GPP at sites where there is bottom-up control of primary production on the food web can provide important management-relevant information. We employed a similar semi-mechanistic model to that used at Diamond Creek (Hall and others, 2015) to examine the environmental controls on GPP at the 60 Mile site. In addition to the drivers considered at Diamond Creek, we added SRP concentrations being exported from Glen Canyon Dam. We find that SRP is nearly as strong a lever on primary production as is the seasonal variation in light (Figure E.2.1b). Future work will employ this semi-mechanistic modeling approach at other sites along the river to better discern whole-ecosystem drivers.

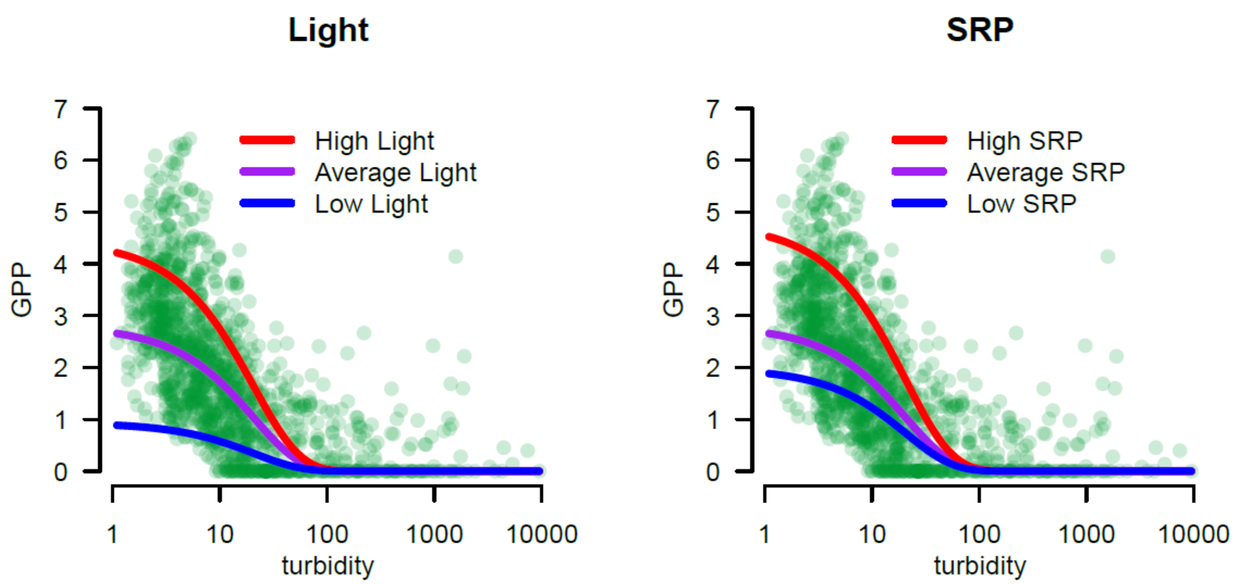

Figure E.2.1b. Rates of gross primary production (GPP) across a range of turbidity values in the river reach above 60 Mile. The lines represent the relationship between turbidity and gross primary production across high, average, and low light conditions (left) and soluble reactive phosphorus (SRP) concentrations released from Glen Canyon Dam (right). SRP at the outflow of Glen Canyon Dam is a similarly strong lever on GPP as is light availability ~120 km downstream. GPP is in units of g O_2 m^{-2} d^{-1} and turbidity is in Nephelometric Turbidity Units.

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 drought 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 E.2.2a). The next step in this process is to continue to build a library of images of vegetation types from August 2016 images and with subsequent trips starting in 2019, and then use those images to develop a fully connected neural network model. 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.

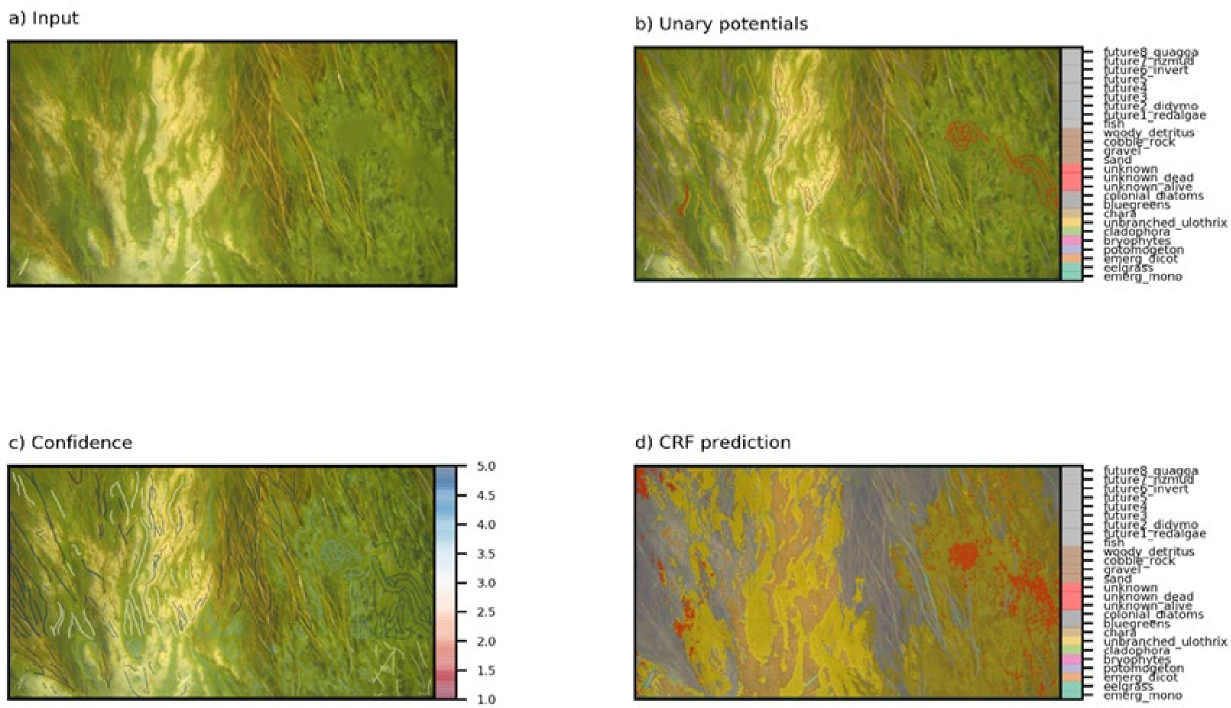

Figure E.2.2a. a) Underwater image taken in Lees Ferry (i.e., the input file); b) Manual on-screen image annotations that classify vegetation types at the pixel level (i.e., unary potentials); c) Confidence assigned to each unary potential by the manual annotator in "b"; and d) Predictions of vegetation cover classes using conditional random fields (CRF), a classification and graphical modeling technique.

Sub-element E.2.3.

We set up 12 replicate fiberglass raceways near the NPS Water Treatment Plant and Maintenance Shop in Lees Ferry (Figure E.2.3a) 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. Each recirculating tank is fed by water coming directly from the Colorado River. River water originates from an intake pipe in the Colorado River ~200 meters away and flows through a system of underground pipes, bypassing the water treatment plant completely. River temperatures at Lees Ferry are stable, fluctuating by < 3°C daily, but water temperatures in our research tanks vary significantly more than the mainstem Colorado River. River water warms by a few degrees when flowing through the pipes, resulting in high starting temperatures, and then solar radiation and high air temperatures aboveground result in large daily water temperature fluctuations in the tanks.

Figure E.2.3a. Artificial stream experiment tank configuration adjacent to the National Park Service Water Treatment Plant in Lees Ferry. Untreated water is drawn from underground pipes coming from the Colorado River ~200 meters away.

We have experimented with mechanisms to keep the tanks cool, including the use of chillers, foam covers, and heat exchangers (placed in the large NPS sump), but water temperatures still fluctuate by 10 °C daily in May and 7 °C daily in October, with afternoon water temperatures exceeding 20 °C in May and 16 °C in October even with the most drastic temperature reduction strategies (chiller set to 10 °C and foam insulation covering ¾ of each tank; Figure E.2.3b). The level of effort to reduce the range in temperatures necessitates a large amount of energy that has shorted the electrical system and turned the chillers off, allowing the tanks to warm significantly (see October, Figure E.2.3b). To be successful at this study location we would need to invest a large amount of money in upgrading their power supply.

The current research setup will not produce results that can be directly applied to the management of the Colorado River ecosystem as originally envisioned in the FY 2018-2020 TWP as we are unable to replicate Colorado River conditions at Lees Ferry during the spring, summer, or fall months. We have explored alternate options for this research including placing the tanks on the Glen Canyon Dam "lawn" adjacent to the dam, but Reclamation has raised security concerns that make this setup impossible. In addition, we have asked the NPS if we could place the tanks on the bank of the river but that too was not permissible. We could construct a floating research lab that could be anchored to the riverbed or river banks, but this option has many logistical and permitting constraints and we do not have the funds to build such a laboratory. The remaining option is to move the tanks back to Flagstaff, AZ and answer research questions in a controlled setting at the U.S. Forest Service, Rocky Mountain Research Station facilities currently used by GCMRC. In the coming months the PIs of this project will explore this last option and discuss the utility of these data for the management of the CRe.

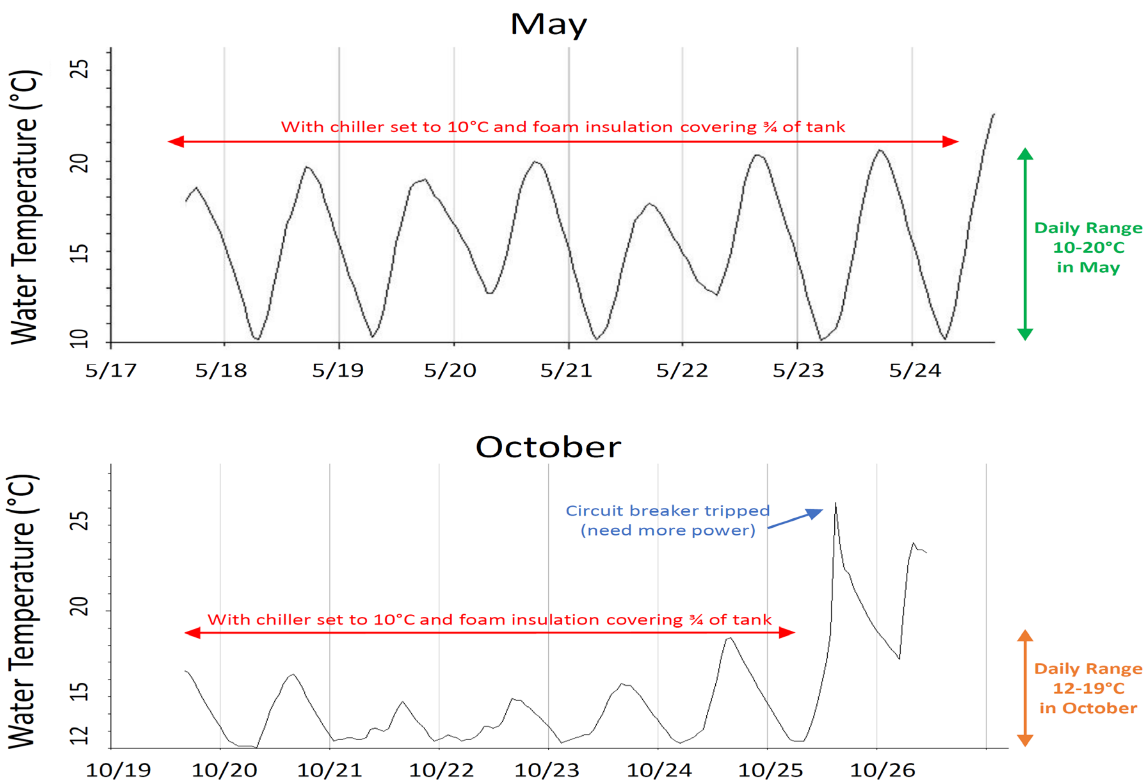

Figure E.2.3b. Temperature loggers were placed in tanks having a variety of temperature control mechanisms. These two plots represent the most extreme measures to control temperatures in the tanks, including placing a chiller in each recirculating tank with a foam insulation pad covering ¾ of the tank. 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.

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. We had hoped to make progress on this sub-element in the winter and spring of 2017-2018 but were instead engaged in developing a brown trout model in support of the 2017 brown trout workshop and subsequent report (Runge and others, 2018). We anticipate more progress in FY 2019.

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, http://dx.doi.org/10.1111/j.1365-2435.2005.00952.x.

Bowes, M.J., House, W.A., Hodgkinson, R.A., and Leach, D.V., 2005, Phosphorus-discharge hysteresis during storm events along a river catchment: The River Swale, UK: Water Research, v. 39, no. 5, p. 751-62, https://doi.org/10.1016/j.watres.2004.11.027

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, http://dx.doi.org/10.1890/03-9000.

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.

Cohen, M.J., Kurz, M.J., Heffernan, J.B., Martin, J.B., Douglass, R.L., Foster, C.R., and Thomas, R.G., 2013, Diel phosphorus variation and the stoichiometry of ecosystem metabolism in a large spring-fed river: Ecological Monographs, v. 83, no. 2, p. 155-176, https://doi.org/10.1890/12-1497.1.

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.

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, p. 936-943, http://www.elserlab.asu.edu/pdf/Elser_ecollet2003.PDF.

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, http://dx.doi.org/10.1002/lno.10031.

Harrison, J.A., Matson, P.A., and Fendorf, S.E., 2005, Effects of a diel oxygen cycle on nitrogen transformations and greenhouse gas emissions in a eutrophied subtropical stream: Aquatic Sciences, v. 67, no. 3, p. 308-315, https://doi.org/10.1007/s00027-005-0776-3.

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.

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.

Vernieu, W.S., 2009, Historical physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964-2013: U.S. Geological Survey Data Series 471, 23 p., http://dx.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, http://dx.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, http://dx.doi.org/10.1038/nature11205.

PRODUCTS/REPORTS					
Type	**Title/Citation**	**Due Date**	**Date Delivered**	**Date Expected**	**Comments**
Journal article	Dibble, K.L., C.B. Yackulic, T.A. Kennedy, J.C. Schmidt, and K.R. Bestgen, Not too hot, not too cold, but just right—The importance of managing for unnatural temperature regimes in the Colorado River: Frontiers in Ecology and the Environment (anticipated submittal December 2018).		To be submitted Dec 2018		
Presentation	Yackulic, C.B., B. Deemer, M. Yard, K.L. Dibble, T.A. Kennedy, and R.O. Hall, 2018, Drivers of the aquatic ecosystem in the Grand Canyon—the relative importance of flows, biotic interactions, temperature and nutrients.		Feb 2018		Invited Talk – Utah State University.
Presentation	Yackulic, C.B., B. Deemer, M. Yard, K.L. Dibble, T.A. Kennedy, and R.O. Hall, 2018, Drivers of the aquatic ecosystem in the Grand Canyon—The underappreciated significance of phosphorous and the future of water temperatures.		Sept 2018		Invited Talk – Northern Arizona University.

Project E Budget

Project E	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$175,026	$7,000	$97,771	$10,000	$0	$43,828	**$333,625**
Actual Spent	$175,133	$1,238	$36,192	$10,000	$0	$33,368	**$255,931**
(Over)/Under Budget	**($106)**	**$5,762**	**$61,579**	**$0**	**$0**	**$10,460**	**$77,694**
						FY18 Carryover	**$77,694**

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

- Travel was low because some field work did not occur, and travel to conferences was covered by outside sources
- Operating expenses were low due to a delay in determining which was the most effective sampling equipment for the research. Carryover funds will be spent in FY2019 to purchase all necessary equipment.

Project F: Aquatic Invertebrate Ecology

Project Lead	Theodore Kennedy	**Principal Investigator(s)** (PI)	Theodore Kennedy, USGS, GCMRC Jeff Muehlbauer, USGS, GCMRC Anya Metcalfe, USGS, GCMRC Morgan Ford, USGS, GCMRC Charles Yackulic, USGS, GCMRC Mike Dodrill USGS, GCMRC Christina Lupoli, Ariz. St. U.
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SUMMARY

Overview

The principal goal of our work this year was to track invertebrate population response to the Bug Flow experiment that was tested from May-August 2018. We designed the Bug Flows hydrograph in collaboration with Western Area Power Administration (WAPA) and Reclamation staff. We monitored the Bug Flow experiment by launching river trips in spring and fall, through continuation of long-term citizen science monitoring in Grand Canyon, and continuation of drift and insect emergence monitoring in Glen Canyon. Additionally, we continued food base data collections in reaches where humpback chub populations appear to be growing (see Project G). We also collected data to understand the food web effects of trout removal and humpback chub reintroduction in Bright Angel Creek, we provided staff for rainbow trout and humpback chub monitoring trips in Grand Canyon and the Little Colorado River, and we participated in writing a synthesis on the status and trends of brown trout (*Salmo trutta*) in Glen Canyon.

Accomplishments

In FY 2018 our group worked with Reclamation, WAPA and others to design and implement the hydrograph for the Bug Flows experiment (see Figure 1). 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. We then built a model to predict the response of the aquatic food base to Bug Flows based on this hydrograph, a downstream flow routing model, and current knowledge of the distribution of aquatic insects throughout the Colorado River ecosystem (see Figure 2).

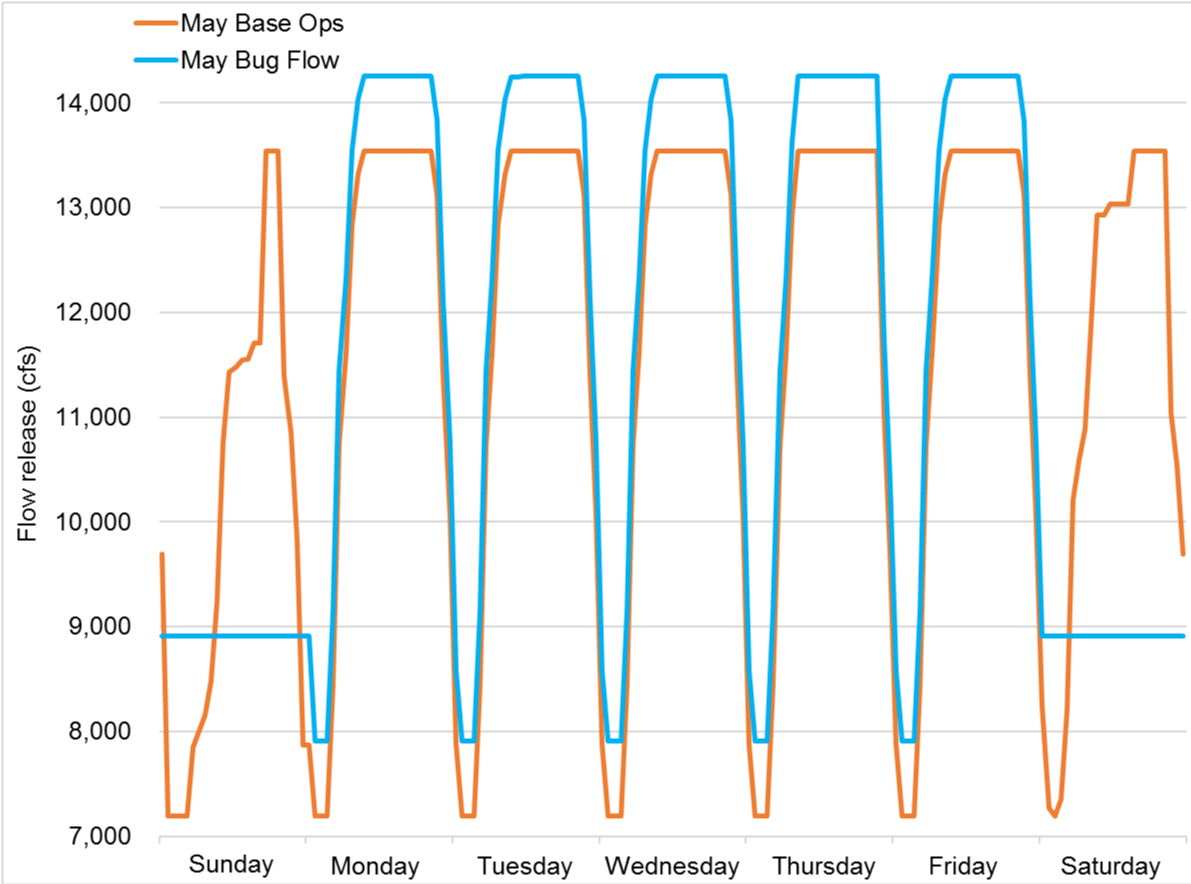

Figure 1. Hydrographs showing flow releases from Glen Canyon Dam under base operations with weekend load-following fluctuations (as if there were no Bug Flow experiment), and under Bug Flow experimental releases with steady, low weekend flows. These hydrographs are for a standard week in the month of May 2018; magnitudes varied across other months, but the pattern was similar.

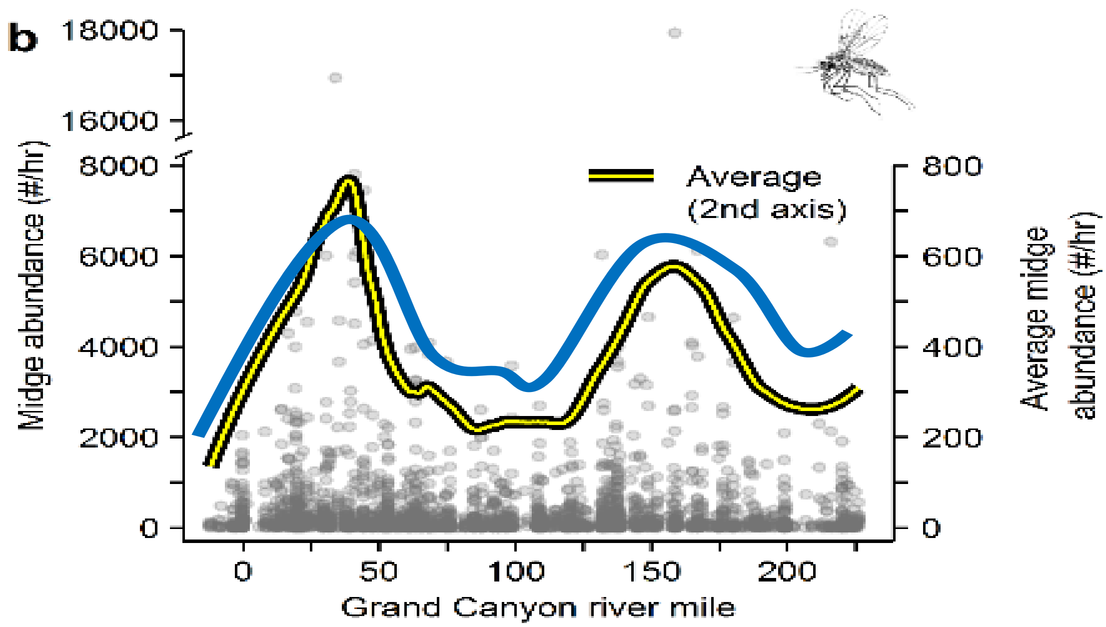

Figure 2. Plot showing observed midge (Chironomidae) distributions throughout Glen, Marble, and Grand Canyons (points and yellow trend line), with the predicted Bug Flows response (blue line) based on our coupled hydrological routing-insect distribution model. Canyon-wide, a 26% increase in midges is expected as a result of Bug Flows once the ecosystem adapts to this novel flow regime.

To study the effects of Bug Flows, we launched two Grand Canyon river trips, one in spring and one in fall. The objectives of these 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 midges and other taxa compared to similar drift data that was collected in 2017. Drift sampling river trips ultimately yielded 143 drift samples, which we expect to finish processing in spring 2019. Citizen science light trapping of adult aquatic insects has been ongoing since 2012, and this dataset will also be used to determine invertebrate response to the Bug Flow experiment. Citizen science yielded 981 light trap samples in 2018, and we anticipate completion of sample processing in January 2019 and a presentation of these results at the February 2019 Annual Reporting Meeting. Citizen scientists also collected acoustic bat data paired with 422 of these traps, which 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.

We also used time lapse photography to determine whether Bug Flows improved egg laying conditions for aquatic insects in Glen Canyon, as hypothesized (see Figure 3). Cameras were deployed at key locations in Glen Canyon thought to be ideal for egg-laying and where such egg laying would also be visible in photographs. These tended to be on large emergent rocks, such as at Honey Draw (RM -13). Photos were taken at 10-minute intervals from early May, just before the start of Bug Flows, and throughout the summer. These photos allow us to visually quantify egg laying at dawn, dusk, and throughout the day, both during routine load-following operations on weekdays and on low, steady discharge weekends throughout the Bug Flows experiment (see Figure 1 for Bug Flow hydrographs).

Figure 3. Photograph showing midge (Chironomidae) eggs laid at steady, low water at RM -13 in Glen Canyon on Sunday, May 6, 2018 during the first weekend of Bug Flows experimentation. Egg strands are the bright white bands in the photo, and likely represent millions of eggs.

Our group continued long-term monitoring of the aquatic food base with monthly drift and sticky trap sampling from Glen Canyon Dam (RM -15.7) to Badger Rapid (RM 8). This Lees Ferry monthly monitoring yielded 1,064 sticky trap samples and 141 drift samples. Drift and sticky trap sample processing for all prior years is complete and samples from 2018 are on schedule to be completed in early 2019 and available for inclusion in our annual reporting meeting presentation. 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.

We are also collaborating with Arizona State University PhD candidate Christina Lupoli to identify the extent to which aquatic resources (e.g., adult aquatic insects) fuel riparian food webs. Lupoli has been conducting field work in Marble and Grand Canyons since 2016. To date, she has collected 528 non-lethal tissue samples from riparian insect consumers including rodents, bats, lizards, and amphibians. Many of these samples were collected on Grand Canyon Youth river trips. Lupoli has also collected samples of aquatic and terrestrial plants and invertebrate primary consumers. Samples will be analyzed for stable isotope ratios of carbon, nitrogen, oxygen, and hydrogen. These isotopic data will be analyzed using mixing models to determine the relative contribution of aquatic versus terrestrial resources to riparian consumers and food webs. Lupoli also received a National Geographic Young Explorer grant that will be used to extend her research on the role of aquatic resources in riparian food webs to the Green River in Flaming Gorge, UT. Lupoli is currently processing her samples from the 2018 field season.

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, and rainbow trout feeding habits to the Bug Flows experiment. Sampling occurred from August 10-13 (Friday-Monday) and included two days with load-following flows (August 10 and 13) and two weekend days with low steady discharges for Bug Flows (August 11 and 12). On each day, invertebrate drift samples were collected at four sites (RM -12.9, -8, -3.5, and 0) and at three different times of day (~6am, 8am, 3pm). On weekdays during load-following, the three sample times correspond to low, medium (rising limb), and high (on-peak) discharge while during weekend Bug Flows the three sample times correspond to identical, low discharges. Drift sample processing from this experiment is ongoing.

These data will allow us to identify whether Bug Flows affect short-term invertebrate drift concentrations compared to routine load-following, although these results will be confounded by a transmission line outage on August 12 that resulted in flow releases unexpectedly dropping on that day rather than remaining steady. Insect emergence was also quantified daily from August 10-13. These data have already been processed and were presented at the August AMWG meeting. These sticky trap data demonstrate that emergence of adult midges was significantly higher during weekend Bug Flows compared to weekdays with load-following flows (see Figure 4). Finally, rainbow trout diet samples were collected daily from August 10-13 using non-lethal gastric lavage. Rainbow trout were captured for this diet study with the help of volunteer anglers. Diet sample processing is ongoing and will ultimately be used to determine whether energy intake or feeding habits of rainbow trout differ between weekday load following flows compared to weekend Bug Flows.

Our group also provided support staff on rainbow trout monitoring (Project H) and juvenile chub monitoring (Project G) trips in FY 2018. On rainbow trout monitoring efforts in Glen Canyon we collected rainbow trout diet samples that are being used to identify prey preferences (see next paragraph). On juvenile chub monitoring trips we collected invertebrate drift, sticky trap, and light trap samples to characterize the aquatic food base at both the Little Colorado River confluence (RM 62) and Fall Canyon (RM 211) reaches. Sampling on humpback chub trips yielded 42 drift samples, which we expect to finish processing in mid-2019.

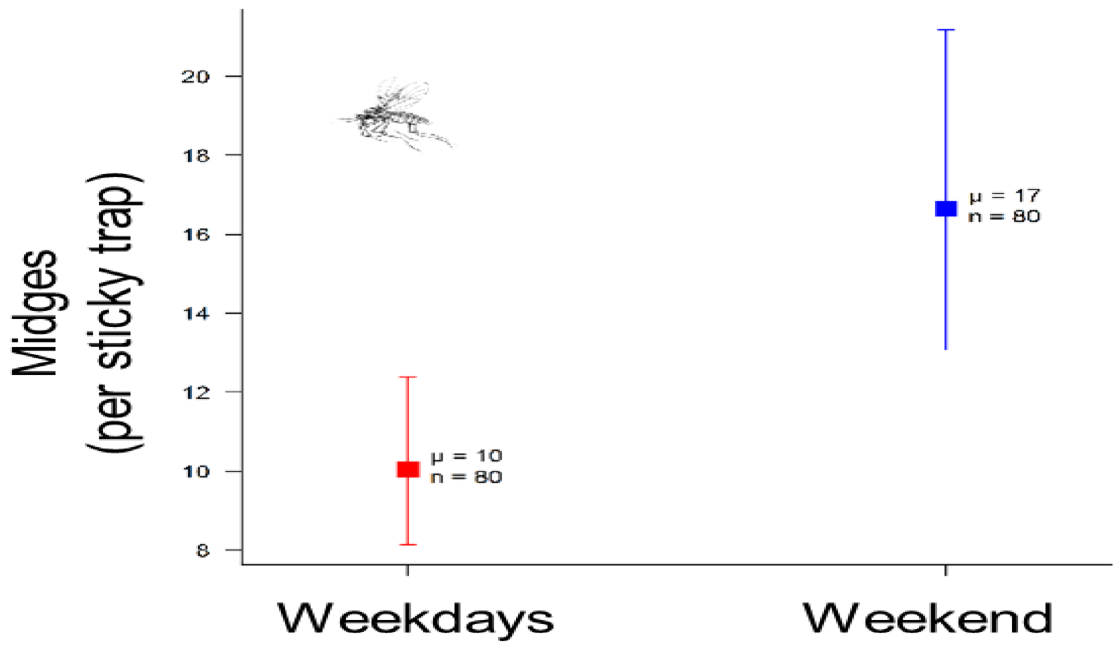

Figure 4. Graph showing emergence of adult midges from the Colorado River in Glen Canyon is significantly greater on weekends during Bug Flows compared to weekdays when flows fluctuate associated with hydropower production. The point represents the mean value (μ), n= sample size, and the error bars represented one standard error. These differences in catch rates of midges between weekdays and weekends are statistically significant (t-test, p-value < 0.0001).

To understand rainbow trout foraging dynamics, we are developing a Bayesian discrete choice model that integrates invertebrate drift monitoring and rainbow trout diet data. Using 784 drift samples and 1028 rainbow trout diet samples to characterize prey availability and fish consumption, respectively, we are comparing the species and sizes of invertebrates found in the drift relative to the invertebrates that are consumed by rainbow trout. This allows us to understand which species of prey are preferred and which are avoided. This modeling approach also allows us to include environmental covariates, such as turbidity, which can drastically change the foraging environment of drift foraging sight feeders like rainbow trout. Describing invertebrate prey preferences and how environmental factors affect rainbow trout foraging improves our ability to predict how changes in the food base, such as are expected with Bug Flows, will propagate through the food web and affect rainbow trout populations.

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 2018. Our sampling approach is based on the design used by Whiting and others (2014, *Freshwater Science*) that was used to sample aquatic invertebrates in Bright Angel Creek prior to trout removal. We sampled aquatic invertebrates in Bright Angel Creek twice in FY 2018 (June and September). In total, we collected 40 benthic, 18 drift, and 40 sticky trap samples of aquatic insects in the 1600-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 first goal in FY 2019 is to finish processing samples collected in FY 2018 prior to the Annual Reporting Meeting in February, and our lab is currently on track to meet this goal. Collectively, the data from these samples will allow us to quantify the effects of Bug Flows on the aquatic food base in Glen, Marble, and Grand Canyons, and the extent to which this flow experiment has been successful in improving food availability for fish during this first year of experimentation. Results from these data will also be useful in facilitating decision-making with respect to whether to carry out a second year of Bug Flows experimentation in 2019 and if any modifications to the design of Bug Flows (e.g., seasonality, weekend flow level) might be useful in 2019 and future years.

We also anticipate launching one or two river trips in FY 2019 that will mirror drift-specific trips carried out in the spring and fall of FY 2017 and 2018. These data will be useful in describing the response of the aquatic food base to the FY 2018 Bug Flows, as they will represent “post-experiment” samples to be contrasted with the “pre-experiment” samples collected prior to Bug Flows experimentation.

Contingent on funding and testing the Bug Flow experiment again in 2019, we may also attempt to carry out a repeat of the intensive weekday-weekend study described above to more fully characterize how Bug Flows affect aquatic resources on a daily scale. This study in FY 2018 yielded some interesting and unexpected results that shed light on how Bug Flows may be affecting aquatic insect behavior but was confounded by emergency dam flow management changes occurring on the weekend of the study that make strong inference difficult.

A repeat of this study, either in the Glen Canyon reach or downstream in native fish reaches (e.g., the Little Colorado River and Fall Canyon chub sampling reaches) would therefore be useful if Bug Flows are tested again in 2019.

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, and our drift sampling concomitant with juvenile chub monitoring and rainbow trout monitoring trips (see projects G and H). Collectively, these data provide important insight into the long-term status and trends of the aquatic food base in the CRe, particularly as it pertains to food resources for rainbow trout and humpback chub. As noted above, these data are also useful in addressing the effect of Bug Flows experimentation on these resources.

Additionally, we will continue collaborating with citizen science river guides and Arizona State University PhD student Christina Lupoli to quantify the extent to which the aquatic food base also structures nearshore terrestrial communities and ecology. Lupoli has an additional summer field season of data collection left to carry out and will then close out FY 2019 by entering the writing stage of her PhD dissertation with results forthcoming in FY 2020. We will also begin synthesizing linked light trap and acoustic bat data collected by the citizen science river guides over the past two years to ascertain whether there is a link between aquatic insect abundance and bat foraging activity. This information will be useful in more fully describing the ways in which aquatic food base resources affect the ecology and resources of interest of the entire Colorado River corridor in Grand Canyon.

Finally, we expect to convene a protocol evaluation panel (PEP) in FY 2019, ideally in May, during what would be the start of another year of Bug Flows (assuming the experiment is carried out again this year). The last food base PEP was carried out in 2012 and resulted in fundamental changes to the aquatic ecology program, including the initiation of citizen science light trapping, changes to drift sampling, and the start of sticky trap sampling, all of which are now a critical part of our monitoring and research program.

That PEP also laid the groundwork for what would become our *BioScience* paper (Kennedy and others, 2016), which eventually led us to Bug Flows experimentation. The ideas and next steps identified in that PEP were useful in guiding the program for the past six years. But the research goals identified in that PEP have been fully realized and new guidance and a critique from a panel of outside experts would be useful in helping us identify next steps for the food base research program. Specifically, in FY 2019, we would ask PEP scientists to comment on the state of our research with respect to Bug Flows experimentation and to provide guidance on potential new ideas and priorities for research in the CRe.

REFERENCES

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, http://dx.doi.org/10.1093/biosci/biw059.

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, http://dx.doi.org/10.1086/676915.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Little bugs, big data, and Colorado River adaptive management		Dec 2017	Dec 2017	Kennedy, T.A., 2017, Little bugs, big data, and Colorado River adaptive management—presentation: Colorado River Water Users Association Annual Meeting: Las Vegas, Nev., December 13-15, 2017.
Presentation	Aquatic invertebrate drift patterns downstream of Colorado River Basin dams		Jan 2018	Jan 2018	Muehlbauer, J.D., 2018, Aquatic invertebrate drift patterns downstream of Colorado River Basin dams—presentation: Colorado River Aquatic Biologists Meeting, Lower Colorado River Multi-Species Conservation Program, Laughlin, Nev., January 10-11, 2018, https://www.lcrmscp.gov/crab/presentations/2018/crab18_21.pdf.
Presentation	Shedding light on aquatic insects of the Colorado River Basin with citizen science		Mar 2018	Mar 2018	Metcalfe, A., Muehlbauer, J., and Kennedy, T., 2018, Shedding light on aquatic insects of the Colorado River Basin with citizen science—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, Flagstaff, Ariz., March 2018.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Bug flow optimizations and predictions		Mar 2018	Mar 2018	Muehlbauer, J., and Kennedy, T.A., 2018, Bug flow optimizations and predictions—presentation: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting: Flagstaff, Ariz., March 2018.
Presentation	Macroinvertebrate production flows: proposed hydrograph and study plan		Mar 2018	Mar 2018	Muehlbauer, J. and Kennedy, T.A., 2018, Macroinvertebrate production flows—Proposed hydrograph and study plan: Webex presentation to Glen Canyon Dam Adaptive Management Program, 2018.
Presentation	Hydropower and the aquatic-terrestrial dynamic downstream of Glen Canyon Dam		Mar 2018	Mar 2018	Lupoli, C.A., Kennedy, T.A., Muehlbauer, J.D., Sabo, J.L. & Yackulic, C.B., 2018, Hydropower and the aquatic-terrestrial dynamic downstream of Glen Canyon Dam—poster: Glen Canyon Dam Adaptive Management Program, Annual Reporting Meeting, Flagstaff, Ariz., March 2018.
Presentation	Possible LTEMP experiment in 2018: macroinvertebrate production flows (bug flows)		Mar 2018	Mar 2018	Grantz, K., VanderKooi, S. & Muehlbauer, J.D., 2018, Possible LTEMP experiment in 2018—Macroinvertebrate production flows (bug flows): WebEx presentation to Glen Canyon Dam Adaptive Management Working Group Experimental Technical Team Meeting, Webinar, March 2018.
Presentation	Invertebrate drift throughout Colorado River Basin tailwaters		Mar 2018	Mar 2018	Muehlbauer, J.D. & Kennedy, T.A., 2018, Invertebrate drift throughout Colorado River Basin tailwaters: Lower Colorado River Science Symposium, Laughlin, Nev., March 2018.
Presentation	Update on proposed 'Bug Flow' Experiment		Apr 2018	Apr 2018	Kennedy, T.A., Metcalfe, A.N., and Muehlbauer, J.D., 2018, Update on proposed Bug Flow Experiment: Grand Canyon River Guides Association, Annual Guides Training Seminar: Marble Canyon, Ariz., April 2018.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Update on proposed 'Bug Flow' Experiment		Apr 2018	Apr 2018	Kennedy, T.A., and Muehlbauer, J., 2018, Update on proposed Bug Flow Experiment—Presentation to Pueblo of Zuni Tribal President, Tribal Council, and Tribal Elders: Pueblo of Zuni, New Mex., April 2018.
USGS Report	Brown trout in the Lees Ferry reach of the Colorado River: Evaluation of causal hypotheses and potential interventions		Apr 2018	Apr 2018	Runge, M.C., Yackulic, C.B., Bair, L.S., Kennedy, T.A., Valdez, R.A., Ellsworth, C., Kershner, J.L., Rogers, R.S., Trammell, M., and Young, K.L., 2018, Brown trout in the Lees Ferry reach of the Colorado River—Evaluation of causal hypotheses and potential interventions: U.S. Geological Survey Open-File Report 2018-1069, 83 p., https://doi.org/10.3133/ofr20181069.
Presentation	Longitudinal drift recovery patterns downstream of large dams		May 2018	May 2018	Muehlbauer, J. and Kennedy, T., 2018, Longitudinal drift recovery patterns downstream of large dams—presentation: Society for Freshwater Science Annual Meeting: Detroit, Mich., May 20-24, 2018.
Presentation	Implementation of macroinvertebrate production flows: Preliminary observations		May 2018	May 2018	Vanderkooi, S. and Kennedy, T.A., 2018, Implementation of macroinvertebrate production flows—Preliminary observations: Webex briefing to Glen Canyon Dam Adaptive Management Program, May 2018.
Journal article	Warm water temperatures and shifts in seasonality increase trout recruitment but only moderately decrease adult size in western North American tailwaters		May 2018	May 2018	Dibble, K.L., Yackulic, C.B., and Kennedy, T.A., 2018, Warm water temperatures and shifts in seasonality increase trout recruitment but only moderately decrease adult size in western North American tailwaters: Environmental Biology of Fishes, v. 101, no. 8, p. 1269-1283, https://doi.org/10.1007/s10641-018-0774-7.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Hydropeaking dams facilitate ecological dominance		May 2018	May 2018	Abernethy, E.F., Muehlbauer, J.D., Kennedy, T.A., Van Driesche, R.P., and Lytle, D.A., 2018, Hydropeaking dams facilitate ecological dominance—presentation: Society for Freshwater Science Annual Meeting, Detroit, Mich., May 20-24, 2018.
Presentation	Update on the progress of the bug flow experiment		Jun 2018	Jun 2018	Kennedy, T.A., and Muehlbauer, J.D., 2018, Update on the progress of the Bug Flow experiment—presentation: Glen Canyon Dam Adaptive Management Program, Technical Work Group: Phoenix, Ariz., June 2018.
Presentation	Does hydropower affect food web connectivity in an arid large-river system?		Aug 2018	Aug 2018	Lupoli, C.A., Kennedy, T.A., Muehlbauer, J.D., Sabo, J.L. & Yackulic, C.B., 2018, Does hydropower affect food web connectivity in an arid large-river system?—presentation: Ecological Society of America Annual Meeting: New Orleans, LA, August 5-10, 2018.
Presentation	Update on the progress of the Bug Flow experiment		Aug 2018	Aug 2018	Kennedy, T.A., and Muehlbauer, J.D., 2018, Update on the progress of the Bug Flow experiment: Glen Canyon Dam Adaptive Management Program, Adaptive Management Working Group, Flagstaff, Ariz., August 2018.

Project F Budget

Project F	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$562,539	$21,650	$32,700	$34,250	$0	$96,997	**$748,136**
Actual Spent	$577,416	$11,567	$56,083	$0	$0	$100,353	**$745,419**
(Over)/Under Budget	**($14,877)**	**$10,083**	**($23,383)**	**$34,250**	**$0**	**($3,356)**	**$2,717**
						FY18 Carryover	**$90,717**

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

- There is an increase in carryover of $88,000, additional funding from Reclamation (GCDAMP Experimental Fund) for aquatic invertebrate studies which will be used to cover salaries for additional technicians in FY2019.
- Salaries exceeded budgeted amount owing to hiring additional technicians.
- Travel was less than budgeted due to missed conference attendance and camping instead of hotel stays.
- Operating expenses exceeded budgeted amount owing to purchase of a powerful microscope for insect identification.
- Cooperative agreements were not awarded due to students securing independent funding.

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 Michael Dodrill, USGS, GCMRC
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SUMMARY

Humpback chub monitoring and research includes both work within the Little Colorado River (LCR) and in neighboring reaches of the Colorado River, where densities of humpback chub are greatest, and in less dense aggregations both upstream and downstream of the LCR confluence. Humpback chub monitoring near the LCR involves sampling both in the tributary itself and at a site in the Colorado River downstream from the LCR confluence known as the east juvenile chub monitoring (JCM-east) site. U.S. Fish and Wildlife Service (USFWS)-led sampling in the LCR (two fall trips and two spring trips) continues to yield abundance estimates from closed models. Effort associated with the JCM-east project was decreased compared to FY 2015-2017 due to budgetary constraints (three trips instead of four and shorter trips), and, in response, we made modest changes to the sampling protocol (increasing the size of the study reach, moving hoop nets more frequently, integrating remote antennas and focusing sampling during months when capture probability should be highest). Data from JCM-east and LCR monitoring will be used to obtain estimates of vital rates (survival, growth) and adult humpback abundances from multistate models. Additionally, we are testing less expensive technology to track humpback chub movement into the LCR and continue to work to integrate these data into population models. Lastly, translocations above Chute Falls occurred as in the past.

Monitoring of humpback chub outside of the LCR aggregation also occurred in FY 2018 – this included aggregation sampling in the Colorado River outside of the LCR, sampling of the Fall Canyon reach in western Grand Canyon (RM 210.5-214.0) using a design similar to that of JCM-east, and a backwater seining trip throughout the Colorado River. Work at the Fall Canyon site is designed to explore the feasibility of applying JCM sampling techniques to estimate vital rates and absolute abundance outside of the LCR. In time, this should lead to stronger inferences regarding drivers of recent increases in downstream humpback chub populations.

Project Element G.1. Humpback Chub Population Modeling

Prior to 2018, humpback chub parameters reported to the GCDAMP stakeholders (e.g., survival, movement, spawning probabilities, and abundance) were obtained from a maximum likelihood version of a multi-state mark-recapture model of adult humpback chub in the LCR spawning aggregation. This maximum likelihood version of the model was limiting because it only included fixed effects of model parameters and the full temporal model was not estimable due to sparse data and low capture probabilities. Thus, some parameters were assumed constant over time and other parameters had to be grouped together *a priori*. Specifically, survival rates were assumed to be temporally constant (i.e., not vary by year) and movement parameters were assumed to be constant within two different periods (2009-2014 and 2015-2017). In 2018, we developed a new version of the multi-state model to estimate adult humpback chub parameters. The new model is a Bayesian model that includes random effects. Random effects allow parameters like survival, movement and growth to vary over time without having to choose pre-defined periods to lump together. This is beneficial for two reasons: 1) we don't have to spend as much time constructing multiple versions of the model in which parameters for different time periods are grouped in different ways and comparing the fit of these different models, 2) temporal trends are driven by the data rather than a combination of the data our decisions about which model structures to consider. Preliminary comparison of the Bayesian and maximum likelihood models indicate that while survival and movement have varied over time, abundance estimates from the two methods are similar (Figure 1), and we are working to incorporate this year's data.

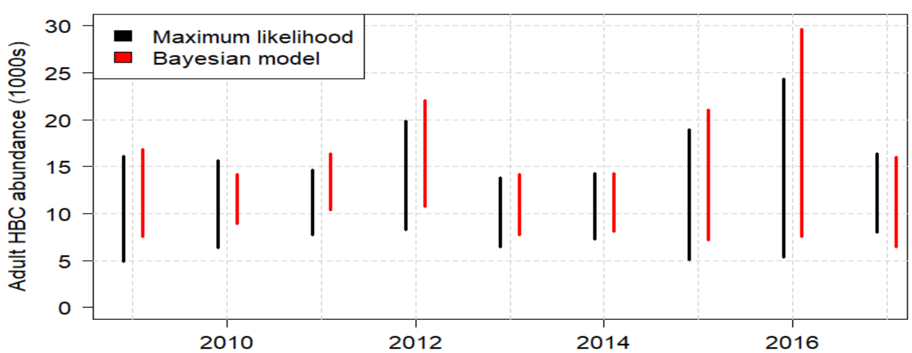


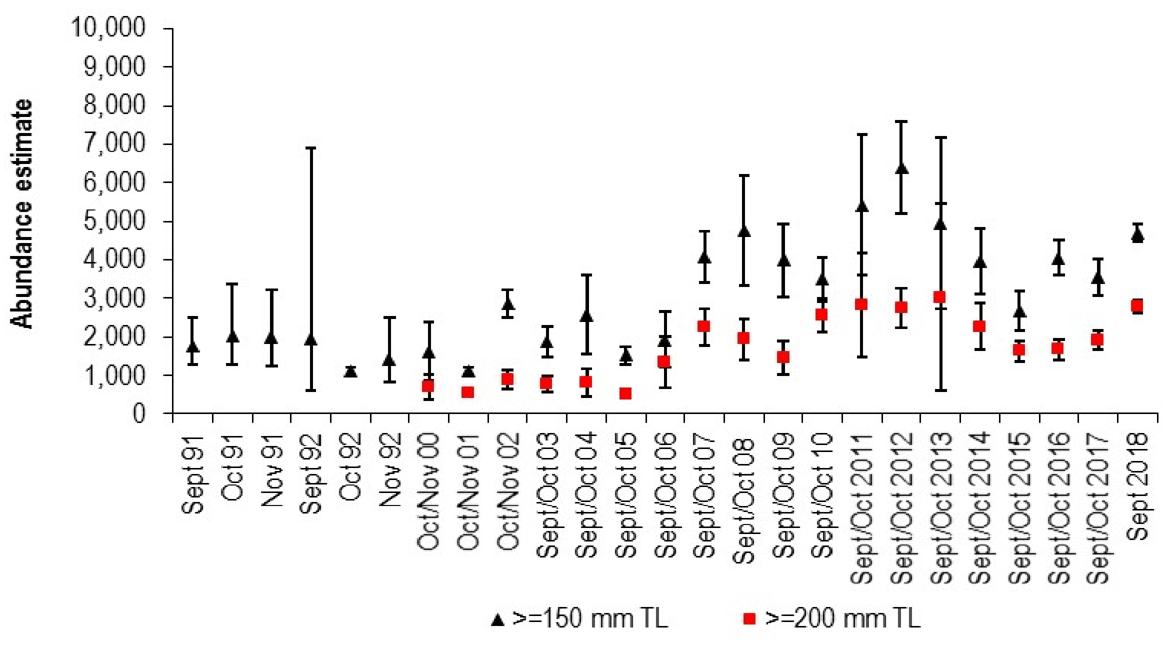
Figure 1. Estimates of adult (≥ 200mm TL) humpback chub abundance for the LCR spawning aggregation. Abundance estimates represent 95% confidence intervals that are estimated using two different methods – a maximum likelihood model (black) and a Bayesian model (red). Importantly, the Bayesian model allows for season-specific estimates of survival and movement, whereas the maximum likelihood model had to assume temporally constant survival rates for four groups of HBC (small adults in the LCR, large adults in the LCR, small adults in the CR, large adults in the CR) and temporally constant movement within two time periods (2009-2014 and 2015-2017). One other notable difference between models is that the Bayesian model was fit using seasonal intervals, whereas the maximum likelihood model was fit using monthly intervals.

In addition, GCMRC and USFWS are currently collaborating to develop a multi-state model to assess the effectiveness of Chute Falls translocations. This model extends the multistate model described by Yackulic and others (2014) to include humpback chub that reside upstream of Lower Atomizer Falls (i.e., upstream of river kilometer (rkm) 13.56). Lastly, we are working with researchers at Colorado State University to develop a model that incorporates demographic (i.e., size and sex) differences in skipped spawning and movement between the Colorado River and LCR.

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

In 2018, USFWS and volunteers conducted three monitoring trips to monitor humpback chub in the LCR. These trips occurred in April, May, and September. A fourth trip, scheduled for October, was cancelled because of inclement weather and severe flooding. The goal of these trips was to monitor the population status and trends of humpback chub in the LCR during spring and fall. During spring 2018, it was estimated that there were 9,768 (Standard Error [SE] = 670) humpback chub ≥ 150 mm total length (TL), of which 7,948 (SE = 617) were ≥ 200 mm TL in the LCR (Figure 2-A). These numbers represent the highest spring abundance of humpback chub in the LCR recorded to date and indicate that, since 2015 and 2016, abundances have increased significantly. The lower estimates in spring 2015 and 2016 are believed to be the result of many humpback chub remaining in the mainstem Colorado River during those years, for reasons unknown.

A.



B.

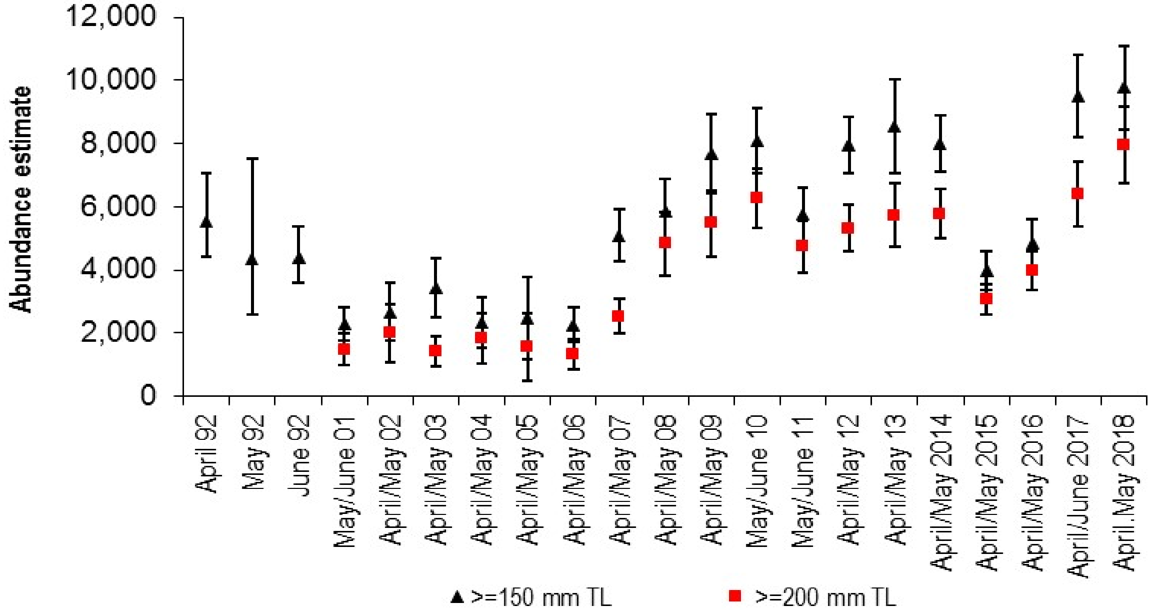


Figure 2. Chapman Petersen abundance estimates (±95% CI) of humpback chub ≥ 150 mm total length (TL) and ≥ 200 mm TL in the Little Colorado River (0-13.57 river km) during (A) spring (2001-2018) and (B) fall seasons (2000-2018). Note: closed spring and fall abundance estimates of humpback chub > 150 mm TL in the Little Colorado River during 1991 and 1992 are from Douglas and Marsh (1996).

Additionally, it was estimated that there were 4,694 (SE=116) humpback chub ≥ 150 mm TL in the LCR during the fall. Of these fish, an estimated 2,779 (SE = 84) were ≥ 200 mm TL. We add the caveat that the fall 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. Lastly, there was a paper published in FY 2018 that informs the ecology of native and nonnative species in the LCR (Stone and others, 2018).

Project Element G.3. Juvenile Chub Monitoring near the LCR confluence

In 2018, there were three JCM trips (occurring in May, July, and October) that visited the Colorado River at the JCM-east site (RM 62.8-65.9) and the Colorado River near Fall Canyon (hereafter called JCM-west; RM 210.5 - 214.0 – see Project Element G.6). In both the JCM-east and JCM-west reaches, two methods (slow-shock electrofishing and hoop nets) were used to capture fish. The protocol for JCM-east and JCM-west sampling was modified slightly from previous years in that the size of the study reach was expanded and there only three passes per site (as opposed to five passes per site in JCM trips prior to 2017). All humpback chub > 79 mm

TL were marked with passive integrated transponder (PIT) tags, and all humpback chub between 40-79 mm TL were marked using visual implant elastomer (VIE). Humpback chub were the most frequently caught species in JCM-east catch (1,164), followed by fathead minnow (1,067), rainbow trout (946), flannelmouth sucker (713), bluehead sucker (393), speckled dace (74), plains killifish (71), carp (47), yellow bullhead (32), channel catfish (13), unidentified suckers (10), brown trout (3), red shiner (2), and green sunfish (1).

In total, all JCM-east trips captured 709 humpback chub > 99 mm TL and 452 chub between 40-99 mm TL. Catch of humpback chub > 99 mm TL was 155 in May, 253 in July, and 301 in October. In addition, catch of humpback chub between 40-99 mm TL was 202 in April, 179 in July, and 71 in October. Catch during the October trip was low, due in part to low abundance of age-0 humpback chub, as well as lower capture probabilities resulting from cold water temperatures (for the season) and high turbidity. Furthermore, there were no humpback chub that were marked in the LCR in July and recaptured in the Colorado River JCM-east site in October. The lack of age-0 humpback chub migrants captured in the JCM-east reach in October is probably due to the low number of humpback chub present in the LCR in summer 2018 (see the Pre-Monsoon Juvenile Chub Sampling in the LCR section below*)* coupled with the lower capture probabilities of JCM sampling.

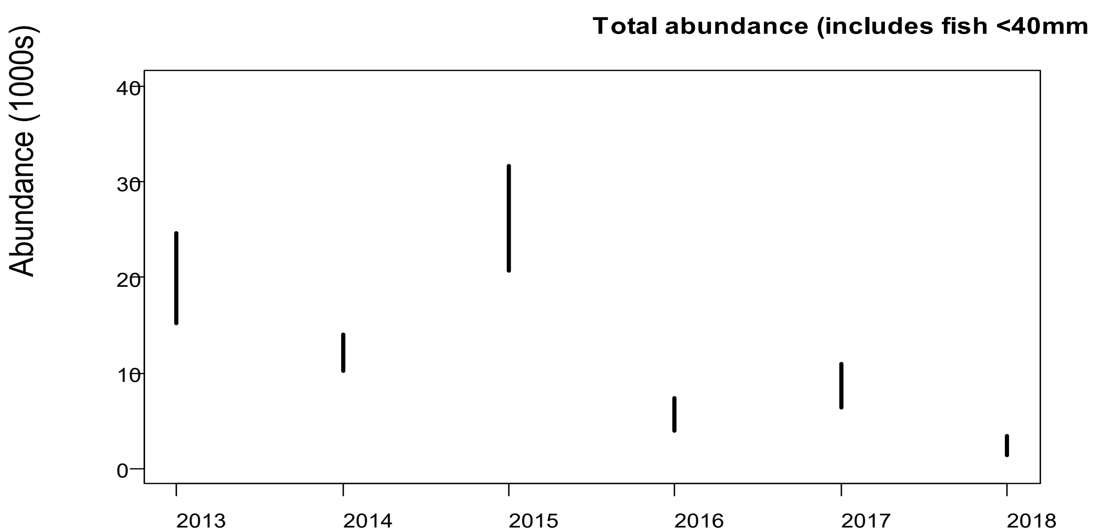


Figure 3. Estimated abundance of age-0 humpback chub (i.e., 40-99mm total length (TL)) during mid-summer sampling trips to the lower 13.6 km of Little Colorado River. Effort was similar in all years.

Pre-Monsoon Juvenile Chub Sampling in the LCR

In 2018, monitoring occurred from June 28 to July 9. As in previous years, three teams completed two passes of the LCR using hoop nets, seines, and dip nets. One change that occurred in 2018 is that all native fish > 100 mm TL captured during the afternoon hoop net haul of pass 1 were not processed (i.e., they were released immediately without scanning for a tag or obtaining measurements). This change occurred as a result of concerns expressed by USFWS that the high afternoon temperatures could stress larger fish. During this trip, 212 humpback chub (40-79 mm TL) were marked with VIE. Catch of age-0 humpback chub in the LCR was low in 2018 compared to previous years, and the abundance for 2018 is the lowest estimated since the start of this project in 2013. Furthermore, the last three years (2016-2018) indicate lower juvenile production in the LCR compared to 2013-2015.

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

Remote Technologies

The LCR multiplexer array (hereafter MUX) is located in the LCR, about 1.7 km upstream of its confluence with the Colorado River. The MUX is comprised of two arrays (*in situ* chains of PIT tag antennas that stretch across the river) 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. The MUX downstream array currently shows very little functionality – only one antenna reliably detects fish and the entire downstream array is currently not functioning (as of September 2018). The MUX upstream array typically has better functionality compared to the downstream array. The upstream array was functioning well in spring 2018 (with 4/6 antennas working) but is down to only one functional antenna as of October 2018. Maintenance is scheduled to occur on the MUX sometime in winter 2019, however, the MUX technology is aging and not supported by the manufacturer so routine maintenance is only somewhat effective.

The MUX detected 8,363 unique PIT tags in FY 2018 (October 1, 2017 – September 30, 2018). Of these unique detections, most occurred in March (2382), followed by April (2242) and May (1450).   Spring months are typically the time when humpback chub migrate into the LCR from the Colorado River to spawn, and accordingly this is the period when the number of LCR array detections is high. Ongoing work is focusing on integrating these data into a multistate population model to improve our understanding of how environmental factors (e.g., flow, temperature) influence survival and movement of humpback chub.

In addition to continuing to maintain the LCR array, USGS and USFWS began testing the use of a network of shore-based individual antennas in the LCR for detecting movements of spawning native fishes. The reasons for deploying this new network design are twofold: 1) The LCR MUX shows signs of malfunction and the equipment it relies on is no longer supported by the manufacturer, and 2) we believe we can improve upon the design of the LCR MUX using a more cost-effective approach. The shore-based network design is still being developed and evaluated for its ability to maximize detection probability. In 2018, we observed that antenna detections were not independent based on our first placement of antennas. Because this non-independence causes considerable bias in abundance estimation, we are in the process of repositioning the shore-based antennas to encompass a larger area in 2019 and remove this bias.

Additionally, JCM-east and JCM-west trips are supplementing mark-recapture data with remote detections by using submersible antennas. Initial results from submersible antennas (from both USFWS and USGS efforts) indicate these technologies are very effective at detecting PIT-tagged humpback chub, particularly larger fish that have low capture probabilities in hoop nets and with electrofishing. Comparison of the number of unique PIT tags detected using antennas and sampling gear types show that antennas substantially augment the number of detections (Table 1), particularly for the JCM-east reach (where the proportion of marked fish is high). Specifically, there were 1,084 unique PIT tags detected on antennas only (and not captured via sampling) in the JCM-east reach during the June 2018 sampling trip.

Table 1. Comparison of the number of unique passive integrated transponder (PIT) tags detected on autonomous PIT tag antennas and sampling gear types (i.e., electrofishing and hoop nets) for the east juvenile chub monitoring (JCM) reach (Table A) and the JCM-west reach (Table B) during the June 2018 sampling trip. Note that unmarked fish can be captured via sampling but are not detectable on antennas. Also note that this does not include fish that are too small to PIT tag (e.g., humpback chub 80+mm total length (TL), flannelmouth sucker and bluehead sucker 150+mm TL).

A.

	Captured during sampling	**Not captured during sampling**
Detected on antennas	93	1,084
Not detected on antennas	755	

B.

	Captured during sampling	**Not captured during sampling**
Detected on antennas	333	310
Not detected on antennas	1,301	

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

Mainstem Colorado River humpback chub aggregations were monitored during an August 21 - September 7, 2018 river trip. Inferences on the status and trends of humpback chub within aggregations is primarily based on hoop net catches, which is used to construct a long term catch per unit effort (CPUE) index. Since 2015, portable antennas have been deployed to supplement information from hoop net catches and detect fish marked with PIT tags (see Project Element G.4). In 2018, fish sampling occurred within the boundaries of several known historic aggregations of humpback chub using both hoop nets and PIT antennas including 30-Mile (RM 30.3-36.4), Little Colorado River Inflow (RM 60-65.4), Bright Angel (RM 86.3-88.3), Stephen Aisle (RM 117.6-120.7), Middle Granite Gorge (RM 126.7-129.8), Havasu (RM 160.4-165.1), and Pumpkin Springs (RM 211-220.7), as well as sampling opportunistically at several localities outside of known aggregations. Several locations in western Grand Canyon, where an increase in humpback chub relative abundance has recently been detected (van Haverbeke and others, 2017), were more intensively sampled to investigate abundance estimation techniques in cooperation with Project Element G.6.

The primary purpose of these annual trips has been to construct a long term CPUE index of humpback chub in the mainstem Colorado River, both within and outside of defined aggregation localities, in fulfillment of LTEMP Biological Opinion conservation measures. A major long-term finding of this study has been that since 2006 there have been significant increases in CPUE of humpback chub at most aggregations as well as at some non-aggregation sites. Additionally, these trips gather information on other members of the fish community across a large section of the Colorado River in Grand Canyon. In 2018, we captured 762 humpback chub, 3,990 flannelmouth sucker, 237 speckled dace, and 6 bluehead sucker with hoop nets. As with the JCM-east and JCM-west studies, we deployed up to eight PIT antennas within each sampling reach and detected PIT tagged fish including humpback chub, flannelmouth sucker, and bluehead sucker. Overall, the sampling strategies and gear used provides timely information on the status of fish populations and informs decisions on both the operation of Glen Canyon Dam and non-flow actions.

Project Element G.6. Juvenile 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). Additionally, the third pass of electrofishing during the October JCM-west trip was not conducted for some sites due to challenging field conditions and logistical problems. As with the JCM-east sampling, the October 2018 trip to JCM-west likely had low capture probabilities due to cold water temperatures (for the season) and high turbidity.

Species composition of catch in JCM-west was comprised mostly of native species, with the highest catch occurring for flannelmouth sucker (24,015), speckled dace (16,559), humpback chub (1,385), bluehead sucker (1,165), and unidentified suckers (831). Non-native catch was comprised of fathead minnow (66), rainbow trout (14), green sunfish (10), carp (8), and plains killifish (6). 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 humpback chub > 99 mm TL was 159 in May, 453 in July, and 118 in October. In addition, catch of humpback chub between 40-99 mm TL was 191 in May, 411 in July, and 45 in October.

Project Element G.7. Chute Falls Translocations

The goals of this project are to:

1. Annually translocate at least 300 juvenile humpback chub from lower portions of the LCR to upstream of rkm 14.2 (i.e., upstream of Chute Falls).
2. Annually monitor the abundance of humpback chub above 13.6 rkm 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 of the LTEMP. Our monitoring activities also coincide with joint efforts with the NPS to collect juvenile or larval humpback chub for transport to the Southwest Native Aquatic Research and Recovery Center (SNARRC), destined to support for 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 humpback chub to upstream of rkm 13.6 in the LCR; intended to increase growth rates and survivorship, expand the range, and ultimately augment the LCR humpback chub population in Grand Canyon. In addition, this project provides managers with an annual index of abundance and trend of humpback chub residing above rkm 13.6.

Translocations

Three efforts to translocate humpback chub were conducted in FY 2018: 1) to the mainstem Colorado downstream of Diamond Creek and Angel Creek, 2) to the LCR upstream of Chute Falls, and 3) to Bright Angel Creek.

Mainstem Colorado River below Diamond Creek and Bright Angel Creek:

In May 2014, 300 larval humpback chub were collected from the LCR with the original purpose of translocation into Shinumo Creek in 2015. However, the Gallahad forest fire in July 2014 precluded further translocations into Shinumo Creek for an unspecified amount of time. Rather, these fish were grown out to adult sizes at SNARRC. In early March 2018, approximately 150 of these fish were released into the mainstem Colorado River near Spencer Creek at RM 246.2. Twenty-three of these fish were implanted with sonic tags. This was followed by tracking efforts in late March, early May, and September 2018. Initially, many of the sonic tagged fish remained near the release site but progressively dispersed to within a few miles both upriver and downriver of the release site as time passed.

Chute Falls:

Efforts to translocate humpback chub upstream of Chute Falls in the LCR have been ongoing since 2003. To date, approximately 3,470 juvenile (~80-130 mm TL) humpback chub have been translocated upstream of Chute Falls. Of these, 49 humpback chub 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 humpback chub. That, combined with LCR flooding during the October 2018 collection effort resulted in an unusually low number of humpback chub being translocated to above Chute Falls. On May 14, 2018, 116 of the fish held at SNARRC were provided to NPS and Reclamation and translocated into Bright Angel Creek.

Monitoring

USFWS and volunteers conduct an annual monitoring trip above 13.6 rkm in the LCR. The purpose of this effort is primarily to monitor the abundance of humpback chub that are translocated to above Chute Falls but also serves to monitor the abundance of humpback chub in a small section of river between rkm 13.6-14.1, 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 humpback chub 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 2010–2018, this set of capture probability data was used to annually estimate the abundance of humpback chub upstream of rkm 13.6 in the Chute Falls and Atomizer reaches (Figures 1 and 2). During a trip in May 2018, we estimated there were 254 humpback chub ≥ 100 mm TL (SE = 17) in the Chute Falls reach. Of these it was estimated that 157 (SE = 10) were adults ≥ 200 mm TL (Figure 1). In the Atomizer reach, it was estimated that there were 173 humpback chub ≥ 100 mm TL (SE = 4). Of these it was estimated that 141 (SE = 3) were adults ≥ 200 mm TL. Results have also indicated unusually rapid growth of translocated fish and high apparent survival.

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 2018 (September 15-27). During this sampling trip, 254 humpback chub were captured ranging from 20 to 101 mm TL. In addition, 2,848 flannelmouth sucker, 1,350 speckled dace, and 124 bluehead sucker were captured. Nonnative fish species were also encountered including common carp, fathead minnow, plains killifish, rainbow trout, and green sunfish. Additionally, we began developing a hierarchical Bayesian model to relate removal sampling used to estimate capture probability with single pass seining (the majority of sampling) across broad riverscape scales. Continued development of novel modelling approaches will aid this project in developing robust long-term assessments of juvenile and nonnative fishes in the Colorado River.

REFERENCES

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

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., 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, http://dx.doi.org/10.1002/ece3.990.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Journal Article	Inferring species interactions through joint mark–recapture analysis.	N/A	FY 2018		Yackulic, C.B., Korman, J., Yard, M.D., and Dzul, M.C., 2018, Inferring species interactions through joint mark-recapture analysis: Ecology, v. 99, no. 4, p. 812-8/21, http://dx.doi.org/10.1002/ecy.2166.
Journal Article	Abiotic controls of nonnative fishes in the Little Colorado River, Arizona	N/A	FY 2018		Stone, D.M., Young, K.L., Mattes, W.P., and Cantrell, M.A., 2018, Abiotic controls of invasive nonnative fishes in the Little Colorado River, Arizona: The American Midland Naturalist, v. 180, no. 1, p. 119-142, https://doi.org/10.1674/0003-0031-180.1.119.
Journal Article	Population expansion of humpback chub in Western Grand Canyon and hypothesized mechanisms	N/A	FY 2018		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.
Journal Article	Effectiveness of ultrasonic imaging for evaluating the presence and maturity of eggs in remote field locations	N/A	FY 2018		Brizendine, M.E., Ward, D.L., and Bonar, S.A., 2018, Effectiveness of ultrasonic imaging for evaluating presence and maturity of eggs in fishes in remote field locations: North American Journal of Fisheries Management, online, https://doi.org/10.1002/nafm.10200.
Journal Article	What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?	N/A	Sept 2018	Nov 2018	Ward D.L, and Vaage, B.M., 2018, *in press*, What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?: Journal of Fish and Wildlife Management.
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., *in press*, Safety in numbers—Applying chance-constrained dynamic programming to population viability analysis and adaptive management: Land Economics.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Journal Article	Integrating standardized catch and mark-recapture data to link flow to recruitment and survival of juvenile fish	N/A		FY 2019	Dzul, M.D., Van Haverbeke, D.R., and Yackulic, C.B., *in review*, Integrating standardized catch and mark-recapture data to link flow to recruitment and survival of juvenile fish: Transactions of the American Fisheries Society.
USFWS Trip Report	Spring 2018 monitoring of humpback chub (*Gila cypha*) and other fishes above Lower Atomizer Falls in the Little Colorado River, Arizona	July 2018	July 2018		Stone, D.M., 2018, Spring 2018 monitoring of humpback chub (*Gila cypha*) and other fishes above Lower Atomizer Falls in the Little Colorado River, Arizona—trip report for May 15-24, 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service, submitted to U.S. Geological Survey Grand Canyon Monitoring and Research Center, Interagency acquisition no. G17PG00059, document no. USFWS-AZFWCO-FL-18-08, 14 p.
USFWS Trip Report	Fall 2018 monitoring and translocation of humpback chub (Gila cypha) in the lower 13.57 km of the Little Colorado River, Arizona—trip report for Sept 18-28 and Oct 24-30, 2018	Dec 2018		Dec 2018	Pillow, M.J., and Stone, D.M., 2018, Fall 2018 monitoring and translocation of humpback chub (*Gila cypha*) in the lower 13.57 km of the Little Colorado River, Arizona—trip report for Sept 18-28 and Oct 24-30, 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service, prepared for U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 11 p.
USFWS Annual Report	Mark-recapture and fish monitoring activities in the Little Colorado River in Grand Canyon from 2000 to 2018	Jan 2019		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 2018: Flagstaff, Ariz., U.S. Fish and Wildlife Service.
USFWS Annual Report	Monitoring humpback chub in the Colorado River, Grand Canyon, August 19-September 4, 2017	N/A	March 2018		Pillow, M.J., Van Haverbeke, D.R., and Young, K.L., 2018, Monitoring humpback chub in the Colorado River, Grand Canyon, August 19-September 4, 2017: Flagstaff, Arizona Fish and Wildlife Conservation Office, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 26 p.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Integrating data to improve understanding and management of rainbow trout and humpback chub in the lower Colorado River		February 2018		Dzul, M.C., Yackulic, C.B., and Korman, J., 2018, Integrating data to improve understanding and management of rainbow trout and humpback chub in the lower Colorado River: 51st Joint Annual Meeting of the Arizona and New Mexico Chapters of the Wildlife Society and American Fisheries Society—presentation, Flagstaff, Ariz., February 2, 2018.
Presentation	Examining the trade-off between computational gains and reduced flexibility when marginalizing discrete latent states in Bayesian population models		July 2018		Yackulic, C.B., Dodrill, M., and Dzul, M., 2018, Examining the trade-off between computational gains and reduced flexibility when marginalizing discrete latent states in Bayesian population models—presentation: Joint Statistical Meeting, Vancouver, Canada, July 29, 2018.
Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA		August 2018		Bair, L.S., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: 149th Annual meeting of the American Fisheries Society, Atlantic City, NJ.
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		September 2018		Springborn, M., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: CU Environmental and Resource Economics Workshop, University of Colorado, Vail, Colo., September 2018.
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		March 2018		Springborn, M., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: UC Davis Center for Population Biology Seminar Series, University of California, Davis, Calif., March 2018.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		June 2018		Donovan, P., 2018, Safety in numbers—Cost-effective endangered species management for viable populations: Western Economics 93rd Annual Conference, Vancouver, British Columbia, Canada, June 2018.

Project G Budget

Project G	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$397,323	$2,000	$60,000	$487,266	$0	$86,075	**$1,032,664**
Actual Spent	$403,739	$9,621	$57,812	$490,100	$0	$88,003	**$1,049,275**
(Over)/Under Budget	**($6,416)**	**($7,621)**	**$2,188**	**($2,834)**	**$0**	**($1,928)**	**($16,611)**
						FY18 Carryover	**($16,611)**

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

- Salary was high because additional technicians were needed for humpback chub monitoring trips.
- Travel was high because costs associated with trip personnel on long duration monitoring trips and other travel was not budgeted accurately.

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
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SUMMARY

Protection of the endangered humpback chub near the LCR remains as one of the highest priorities of the GCDAMP, but a concurrent priority 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 LTEMP EIS (U.S. Department of the Interior, 2016a) and were a major consideration when developing GCD operations and experimental flows included in the selected alternative and LTEMP ROD (U.S. Department of the 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 humpback chub 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 2018-2020 TWP is a new research project called Trout Recruitment and Growth Dynamics (TRGD). The data collection and analyses are 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 LCR, 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 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 mile sub-reach) five times a year. For purposes of study replication, these three sub-reaches were established and assigned a 3-km length, the three sub-reaches each contain a combination of low-angle (spawning bars) and high-angle (talus slopes) shoreline; and in sum, these 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 control numbers by the process of removal. In addition to rainbow trout, all fishery data are used for informing the model development for estimating population dynamics in brown trout. Per NPS guidance, brown trout are removed from the lowest sub-reach (-4 mile sub-reach) and monitored in the upper two less populous sub-reaches. In these two non-removal sub-reaches, brown trout are PIT tagged and released unharmed to monitor movement, growth, determine the variation in capture probabilities, and improve understanding of other controlling factors (flows, nutrients temperature, trout density, and size structure) for this species in Glen Canyon. All brown trout removed in other areas are euthanized and put to beneficial use. Lastly, the removal efforts in the -4 mile sub-reach will be used as a secondary measure of removal efficacy.

General Overview

In 2018, a total of 65,019 fish (63,819 rainbow trout; 1,059 brown trout; 130 flannelmouth sucker; 4 green sunfish; 2 walleye; and 5 common carp) were captured by electrofishing across five seasonal sampling trips in Glen Canyon. Overall brown trout catch rates (number of fish caught per km shoreline) remain somewhat elevated compared to 2012-2014, although lower than previously reported catch rates for late-2016 and early-2017 (Figure 1). In 2018, catch rates show a seasonal increase across that is likely due to changes in capture probability and catchability of small fish captured by electrofishing. Factors that are controlling the catchability remain uncertain (Korman and Yard, 2017); however, fish size, fish density, and elevated water temperatures, particularly in the fall season are likely factors responsible for the increase in catchability.

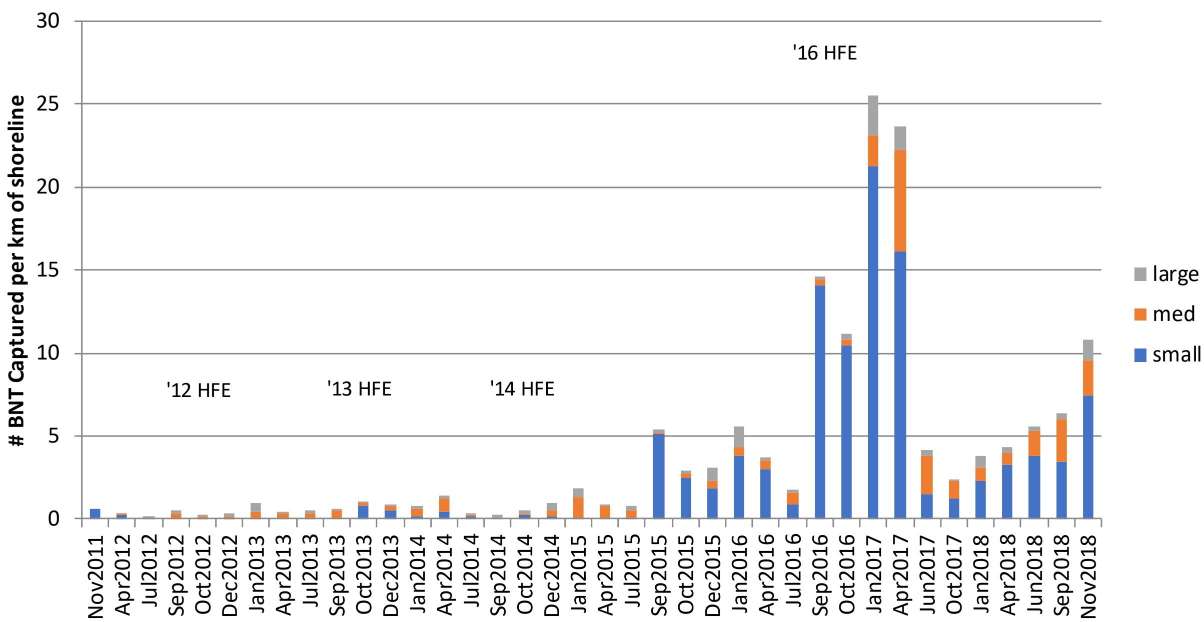

Figure 1. Brown trout seasonal catch rates (number of fish caught per km of shoreline) are based on electrofishing in Glen Canyon, AZ. Size classes are assigned by fork length, small (≤ 200 mm), medium (201 – 400 mm), and large (> 400 mm). The figure indicates years when high flow experiments (HFE) were conducted during the late fall. In 2018, the last catch rate occurred just prior to the November HFE (November 5 – 10, 2018).

A total of 525 brown trout were removed by the TRGD program and were provided to the National Park Service for beneficial use. Current removal efforts within the -4 mile sub-reach do not appear to have influenced overall brown trout catch rates.

Considerable modifications are needed to be made to update the existing Glen Canyon trout population model that was originally developed as part of the Natal Origin Project (Korman and others, 2017) because of the modified sampling layout, sampling frequency, and multiple trout species (brown trout) being modeled. For this reason, the updated population model and other analytical approaches used for evaluating these four study objectives are still being developed. Estimates of trout abundance, recruitment, and vital rates (growth, survival and dispersal rates) are forthcoming and will be reported on at the February 2019 Annual Reporting Meeting. Other types of biometrics like relative abundance and condition factor are reported here to address Project H study objectives.

Variability in electrofishing catch rates across years is partly due to changes in capture probabilities and catchability (density-dependent saturation or changes in fish distributions) (Figure 2). Capture probability is the relationship between the number of marked fish recaptured on a subsequent sampling effort relative to the number of fish originally caught, tagged, and released. The assumption that capture probability remains constant across subsequent sampling trips and years is an important factor when considering the reliability of monitoring relative abundance trends in rainbow catch (number of fish caught per unit time or distance).

Many factors like fish density, size, and temperature (Korman and Yard, 2017, Yackulic *pers. comm.*) will influence capture probability; yet, the critical assumption of constant capture probability is not often asked or tested, and when assessed has been shown to be false, particularly for boat electrofishing in Glen and Grand Canyons (Korman and Yard, 2017). Electrofishing catch rates in Glen Canyon were highly variable across and within years even though estimates of trout abundance of these targeted fish sizes were declining over the same period (Figure 2). Note that catch rates were found to be highly variable from 2012-2014 and only became stable once the rainbow trout population had declined to much lower abundance levels. Seasonal variation in catch rates is likely due to variation in temperature and fish size distributions. Current catch rates are now increasing; however, we are not able to report on whether the actual abundance of catchable-sized fish targeted by anglers is changing, or if this change is due to variation in both capture probabilities and catchability.

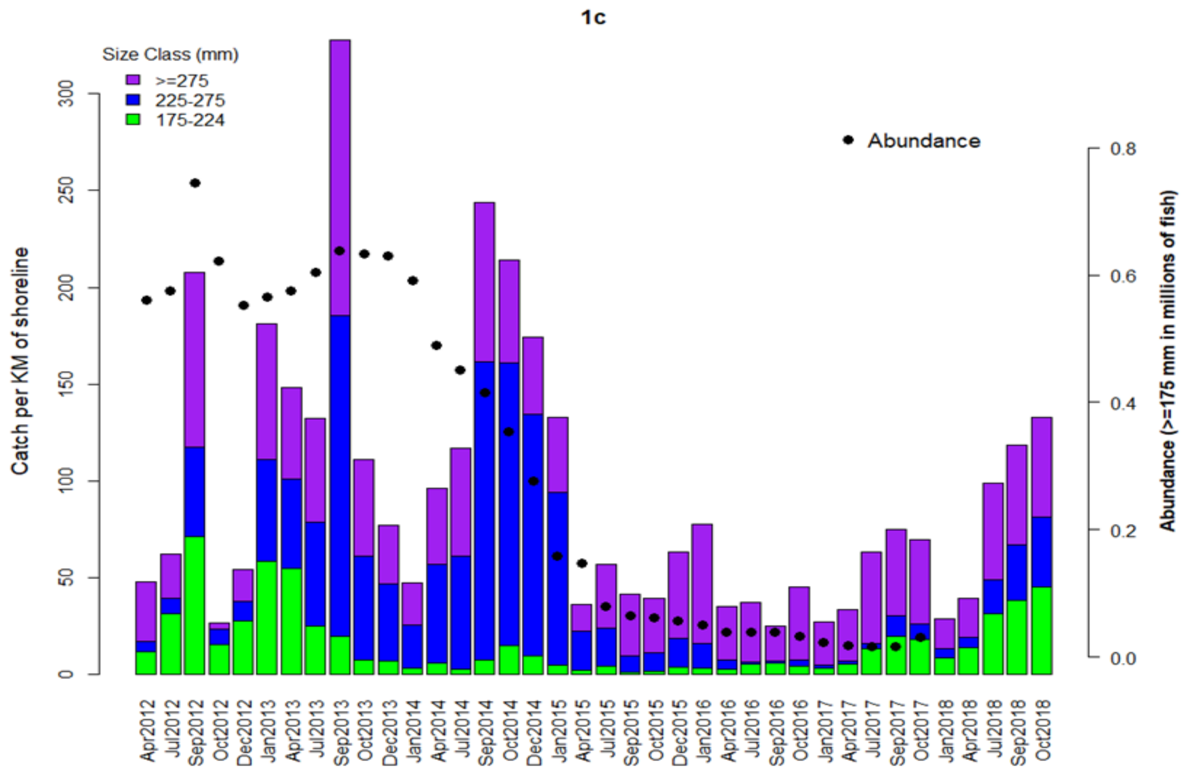

Figure 2. Size-stratified seasonal catch rates of rainbow trout (number of fish caught per km of shoreline) are based on electrofishing in Glen Canyon, AZ. Size classes are assigned by fork length, small (175-224 mm), medium (225 – 274 mm), and large (≥ 275 mm). The black dots are the seasonal abundance estimates totaled for these three size classes, sizes that are equivalent in length to a trout ≥ 200 mm.

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

The analytical design we intend on using 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 of 2018 will require some additional years with and without flow treatments. 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. We will begin reporting on trout growth response to Bug Flows after the 2019 data set is collected. Currently we are using condition factors as a proxy for trout growth.

The recent spring-summer condition factors for rainbow trout suggest good growing conditions that are higher now than in past years, particularly when contrasted with years between 2012 and 2014. Notably though, in 2018 spring-summer condition factors for rainbow trout were similar to condition factors observed in 2016 and 2017, years that had no Bug Flows (Figure 3). More inter-annual data are required to ascertain the effects of stable flows in spring and summer.

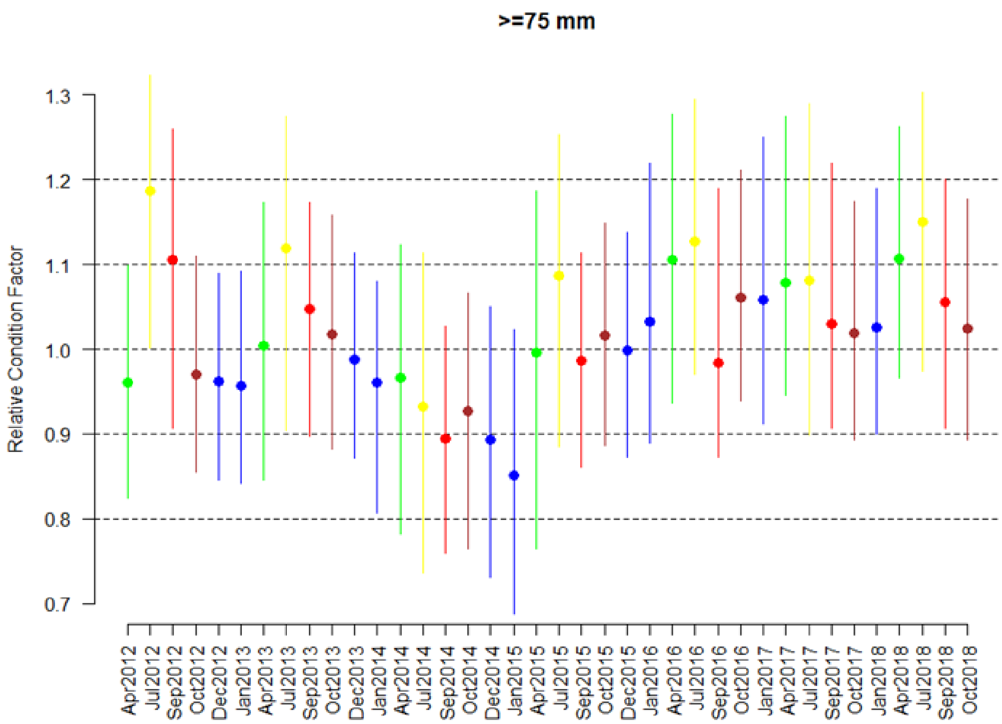

Figure 3. Points represent the relative condition factor of rainbow trout (Size range, ≥ 75 mm fork length) in Glen Canyon between 2012 and 2018. Condition points show the median value, error bars show 80% credible interval. Seasonal sampling trips are symbolized by color: Green = spring (April), yellow = summer (July), red = late-summer (September), brown = fall (October), blue = winter (December and January).

H.1.2. Fall High Flow Experiments

To date, five fall-HFEs have been conducted between 2012 and 2018. 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 two years over this time-period without HFEs (2015 and 2017). Poor fall-winter growth was observed in three consecutive HFE years (2012-2014) across all catchable sized fish (Figure 4, bar and line graphs). Last year 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 a HFE effect on monthly growth rates of rainbow trout (≥ 200 mm FL). However, this was prior to 2017 which we have yet to analyze.

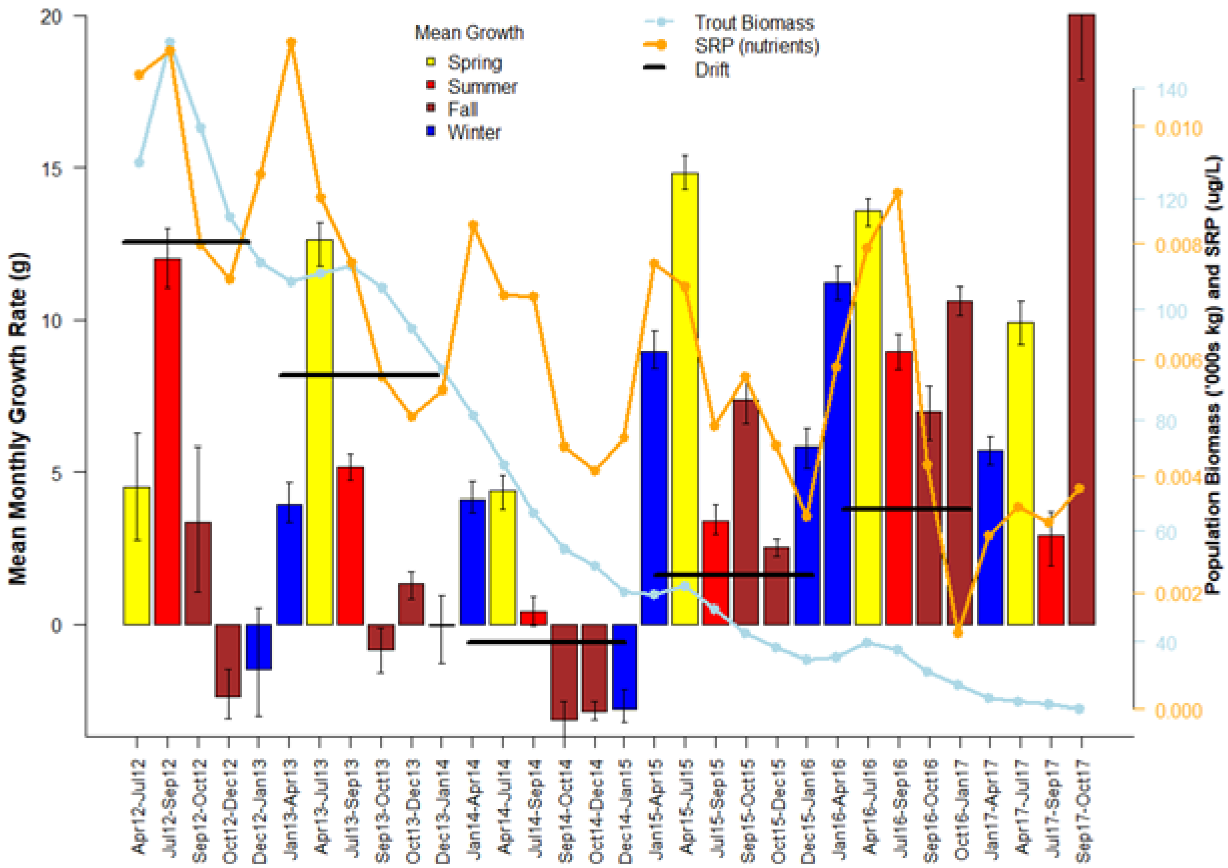

Figure 4. Bar-graph, primary y-axis, is the estimated mean monthly growth rate (g/month, positive or negative) of rainbow trout) (300 mm FL) in Glen Canyon between April 2012 and October 2017. Monthly growth rates are each estimated across the seasonal interval between sampling trips. Each growth interval has been assigned a color: Spring = yellow; Summer = red, Fall = brown, and Winter = blue. Line-graph colored in light blue, second y-axis, is the estimated total population biomass (scale: 1,000 Kg/trip) of average interpolated trip interval averages to daily and average across a trip rainbow trout in Glen Canyon between April 2012 and October 2017. Second line-graph, third y-axis, are the observed soluble reactive phosphorus concentrations (SRP, µg/L) in pen-stocks of Glen Canyon Dam between April 2012 and October 2017.

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 4) 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 suggests a potential HFE effect in that year. However, the current population biomass has continued to decline irrespective of flow events. Until we modify and update the population TRGD model we will be unable to assess the effect of both the 2017 non-HFE and 2018 HFE on rainbow trout growth. Note that there was also a progressive annual drop in SRP (B. Deemer *pers. comm.*) over the first three consecutive HFEs that is strongly correlated that may explain the same phenomena. The effect of these two factors on reduced trout abundance, recruitment, and growth cannot currently be determined.

With respect to trout movement based on recaptures of PIT-tagged fish, there is no indication that taggable-sized fish (≥ 75 mm FL) have moved or were displaced within Glen Canyon by any of the four HFEs conducted between 2012 and 2016. Monitoring to detect any effect of the November 2018 HFE will occur in 2019.

H.1.3. Spring High Flow Experiments

No Spring High Flow Experiments have been implemented to date.

H.1.4. Trout Management Flows

High levels of trout recruitment (age-0) have been shown to lead to poor trout growth and subsequent population collapse that has had negative effects on the trout fishery in Glen Canyon (Korman and others, 2017). Also, high recruitment often leads to higher downstream dispersal of young fish and ultimately negative effects on humpback chub due to higher trout abundance at the LCR confluence (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 in immediate shoreline areas. 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, and hydropower costs. Contingency plans for sampling are in place should a TMF be implemented in the outlying years of this workplan.

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

The primary focus of research in FY 2018 was developing a brown trout model (Runge and others, 2018). The model uses both mark-recapture and catch per unit effort data to estimate brown trout recruitment, growth, and survival. This model served as the basis for comparing evidence of various hypothesized drivers that could be responsible for the recent increases in brown trout. We then coupled this model with previously developed models of rainbow trout and humpback chub population dynamics to simulate the potential impacts of different management scenarios.

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. Tasks 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 to determine their immediate growth response to flow perturbations relative to brown trout survival.

FY 2018 research focused on obtaining age-0 brown trout samples in collaboration with sampling conducted on quarterly TRGD trips. A limited number of fish were captured in April and July 2018 that will be used to determine brown trout hatch and emergence dates. A TMF was not implemented in FY 2018; therefore, we could not collect additional brown trout to examine growth responses to this type of experimental flow. An HFE was conducted in November 2018, but the fall TRGD and AGFD trips sampled fish in Glen Canyon prior to the HFE, so we could not collect brown trout samples post-HFE. In FY 2019, we will increase sampling effort associated with the TRGD and AGFD trips to increase our sample size for projects contained within this sub-element.

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. AGFD used three approaches to monitor the Lees Ferry fishery: 1) boat electrofishing, 2) angler surveys (creel) including the use of a game camera, and 3) a pilot citizen science program with angling guides to measure fish caught by their clients.

Boat electrofishing is 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 (CPUE), 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 conduct two nights of nonnative sampling for each trip within this reach to detect warm water nonnative species (Project Element I.2).

To monitor the status of the Lees Ferry fishery and estimate angler use, AGFD conducted angler surveys to obtain a representative sample of the recreational angling community at Lees Ferry. AGFD uses a stratified random sampling approach to select a subset of days for interviews of both boat and shoreline anglers. Information obtained includes but is not limited to catch rates, gear type, species composition, harvest, and satisfaction with angling experience. Since June 2015, a game camera has been installed at Lees Ferry to record images of the boat launch area and provide a better estimate of boat anglers for the days and hours when a technician is not present.

The pilot citizen science program is an attempt to quantify the exact size of the fish captured by anglers. This is a metric that was included in the Lees Ferry fisheries management plan but cannot be determined from angler surveys.

Summary of Progress

AGFD completed two sampling trips in 2018, sampling 80 monitoring sites and capturing 3,278 fish (excluding the nonnative sampling). Rare nonnatives captured during our normal monitoring were two common carp and 45 brown trout. We conducted angler interviews on 60 days (as of the end of October), and have data from 28 unique trips from the citizen science project. The monitoring activities funded include: one summer electrofishing trip (July 9-13, 2018; 41 standard sample sites, plus an additional 13 sites for nonnatives), one autumn electrofishing trip (September 17-21, 2018; 40 standard sample sites, plus an additional 13 sites for nonnatives), angler surveys - six days each month (four weekend days, and two weekdays), and Citizen Science project (2 guides participating resulting in 28 days of data).

Summary of Trends

H.4.1. Electrofishing

Rainbow trout continue to dominate the fish community within the Lees Ferry reach, comprising 98.1% of the total catch (standard electrofishing), with brown trout comprising 1.66% of the total catch. This is similar to the relative abundance of brown trout in 2017 when brown trout comprised 1.7% of the total catch at Lees Ferry. Rainbow trout have maintained a self-sustaining population since the mid-1990s. Relative abundance, as measured by electrofishing CPUE, has fluctuated greatly since AGFD began standardized sampling in 1991. Rainbow trout CPUE was the highest ever recorded in 2011–2012 but declined from 2012 to 2016. Rainbow trout CPUE in 2018 was similar to that observed in 2017 (3.47 vs. 3.55 fish/minute), with most of the fish captured attributable to YOY rainbow trout (< 152 mm TL). The percent YOY in the fall catch was 60%, with a CPUE of YOY of 2.51 fish/hour (lower than 2017 at 2.75).

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 2018 has been good with the average condition at 1.0 or greater for fish 306-405 mm TL for summer, and autumn. Condition for fish 152-305 mm TL was 1.03 and 0.95 and for large fish (> 405 mm TL) 0.89 and 1.06 for summer and autumn respectively.

CPUE, which AGFD has used as a measure of relative abundance since 1991, is sometimes criticized because capture probability can change due to environmental conditions, spatial distribution of fish, fish size, and population density. To determine whether CPUE data accurately tracks abundance, we compared it with the mark recapture population estimates generated from the Natal Origins project from 2011 to 2016 (Korman and Yard, 2017; Korman and others, 2017). CPUE in Lees Ferry is highly correlated with Natal Origins abundance estimates as measured with a simple linear model, indicating that CPUE does a good job of discriminating changes in the population abundance of the magnitude observed during the 2012-2016 period. A high degree of correlation between CPUE and abundance estimates reflects both the large signal during this period (i.e., a large change in population size) and relatively low noise because of both the consistent environmental conditions (e.g., low turbidity) and efforts to maintain consistent sampling methods.

H.4.2. Angler Surveys (creel)

For angling surveys we use a calendar year to summarize data on angler use, CPUE, and other metrics. At the time of this report (November 2018) we were still collecting angling data and present results based on data from January through October (60 creel days). Boat angler CPUE and 95% confidence intervals for rainbow trout from January through October was 0.88 fish/hr ([95% CI [0.82, 0.94]), while for walk-in anglers it was 0.52 fish/hr (95% CI [0.40, 0.63]). This is lower than the AGFD's goal for the fishery of 1.0 fish/hr, however, it is an improvement over 2017 when catch was 0.71 fish/hr (95% CI [0.66, 0.76]) for boat anglers, and 0.38 fish/hr (95% CI [0.28, 0.48]) for walk-in anglers.

To investigate how bug flows have affected angler success we used our creel data to compare rainbow trout CPUE of boat anglers on days with and without bug flows. Preliminary data shows that angling was better (higher CPUE) for guided boat anglers by about 13.7% during days with Bug Flows and 22.2% for non-guided boat anglers during days with Bug Flows. We hypothesize that more of the river is accessible to anglers and it is easier to fish (place fly/lure where fish are present) and that perhaps fish are not feeding when water level is changing.

As we are still collecting angler use data we only present data from 2017 here. We estimated a yearly relative angler use of 7,025 anglers in 2017, of which 4,593 (95% CI [4,029, 5,158]) were boat anglers and 2,432 (95% CI [2,065, 2,800]) were walk-in anglers. Boat angler use of 4,908 (95% CI [4,470, 5,346]) for 2017 was similar to that in 2016, while the number of walk-in anglers doubled from an estimate of 1,204 (95% CI [1,013, 1,395]) in 2016 to 2,432 (95% CI [2,065, 2,800]) in 2017.

H.4.3. Citizen Science

In 2018 two guides participated, and we received length measurements for 552 rainbow trout captured by 46 anglers over 28 unique fishing trips. Preliminary results show that we are not meeting AGFD's goals for size structure of fish captured by anglers in the Lees Ferry fishery – only 26% of anglers caught at least one 14" rainbow trout per hour, and no 20" rainbow trout were recorded. The average size of fish measured was 12" ± 3.5" (mean ± Standard Deviation), and the largest fish measured was 19." The 2018 citizen science study was a pilot project; in 2019 we hope to sign up additional guides and increase our sample size.

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, http://dx.doi.org/10.1080/00028487.2011.572015.

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, http://dx.doi.org/10.1139/cjfas-2015-0101.

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, http://dx.doi.org/10.1080/00028487.2017.1317663.

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

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

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, http://dx.doi.org/10.1139/cjfas-2015-0102.

PRODUCTS/REPORTS

Type	Title	Due Date	Date Delivered	Date Expected	Citations/Comments
Journal Article	Brown trout in the Lees Ferry reach of the Colorado River: Evaluation of causal hypotheses and potential interventions.				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.
Data Release	Population dynamics of humpback chub, rainbow trout and brown trout in the Colorado River in its Grand Canyon Reach: Modelling code and input data				Yackulic, C.B., Korman, J., and Coggins, L., 2018, Population dynamics of humpback chub, rainbow trout and brown trout in the Colorado River in its Grand Canyon Reach—Modelling code and input data: U.S. Geological Survey data release, https://doi.org/10.5066/F7FN15HC.
Journal Article	Examining the influence of experimental floods on the growth and physiological condition of juvenile rainbow trout.	Aug 23, 2018			Dibble, K.L., and Yackulic, C.B., 2018, Examining the influence of experimental floods on the growth and physiological condition of juvenile rainbow trout—presentation: 148th Annual Meeting of the American Fisheries Society, Atlantic City, NJ, August 19-23, 2018.

Project H Budget

Project H	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$303,552	$0	$25,460	$162,285	$0	$56,053	**$547,350**
Actual Spent	$293,195	$4,686	$9,071	$84,000	$0	$50,273	**$441,226**
(Over)/Under Budget	**$10,357**	**($4,686)**	**$16,389**	**$78,285**	**$0**	**$5,780**	**$106,125**
						FY18 Carryover	**$106,125**

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

- Salary cost was lower than anticipated due to a staff member working part time.
- Travel was planned, but failed to get in the budget by mistake.
- Equipment/supply purchases were delayed in an effort to maximize carryover due to uncertainty about FY2019 funding.
- One cooperative agreement was not awarded in FY2018, but will be in FY2019.

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

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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 that occur in the Colorado River ecosystem from Lees Ferry, AZ to Lake Mead. Lees Ferry monitoring (Glen Canyon Dam to Lees Ferry) is discussed in a different subsection below. The purpose of this program is to obtain a representative sample of the fish community within the Colorado River. Results (species composition and relative abundance measured as CPUE) from our surveys can be used to interpret trends in abundance and distribution of native and nonnative fish throughout the Grand Canyon. Boat electrofishing, baited hoop nets, and angling are utilized in this monitoring program.

Summary of Progress

We completed three mainstem sampling trips in 2018. A stratified random sampling approach was used to obtain a representative sample of the Colorado River fish community that was susceptible to electrofishing or baited hoop nets. A total of 399 sites were electrofished during two spring (April 5-18, April 26 - May 5) system-wide trips, which resulted in the capture of 2,795 fish. Seven samples sites were excluded due to malfunction of equipment or failure to record time spent electrofishing. We set 216 hoop nets during the two spring trips (105 and 113 nets set per trip) capturing 1,137 nonnative fish including 224 humpback chub. The majority of these humpback chub received PIT tags with the exception of 21 fish < 80 mm TL and 28 individuals that had been PIT tagged previously. One wild razorback sucker was captured at RM 243.0 on river right within a small backwater (543 mm TL, 1462 g) along with a flannelmouth-razorback hybrid (549 mm TL, 1338 g). Another flannelmouth-razorback hybrid was captured at RM 115.5 on river left in a hoop net (450 mm TL, 893 g).

During the fall sampling trip (September 27 – October 1) from Diamond Creek to Pearce Ferry Rapid, we captured 1,165 fish from 40 sites over two nights of electrofishing. We only electrofished for two days before turbidity increased to levels too high (> 4,000 NTU) to effectively electrofish. We captured 1,299 fish in 72 hoop nets set over 4 nights. We angled at four camps and only captured two fish, both humpback chub (TL = 311, 341), one was a recaptured fish and the other was not previously tagged.

Flannelmouth sucker dominated the catch for both electrofishing and hoop nets, with 75 and 55 percent of the fish captured, respectively. We captured 159 humpback chub in baited hoop nets set from Lees Ferry to Pearce Ferry Rapid. We believed that high turbidity affected our catch rate, as we set fewer nets (56) and captured more fish (1,788) and more humpback chub (237) in 2017.

Table 1. 2018 catch summaries for the two spring trips by species and gear (BGS = bluegill, BHS = bluehead sucker, BNT = brown trout, CCF = channel catfish, CRP = common carp, FBH = flannelmouth bluehead sucker hybrid, FHM = fathead minnow, FMS = flannelmouth sucker, FRH = flannelmouth razorback sucker hybrid, HBC = humpback chub, PKF = plains killifish, RBS = razorback sucker, RBT = rainbow trout, RSH = red shiner, SPD = speckled dace, STB = striped bass, SUC = undetermined sucker species). Nonnative species are in red font.

GEAR	BGS	BHS	BNT	CCF	CRP	FBH	FHM	FMS	FRH	HBC	PKF	RBS	RBT	RSH	SPD	STB	SUC	Total Result
Angling				1	3			3		1			8					**27**
Electrofishing	1	96	21		27	3	14	1841	1	8	1	1	613	3	158	4	3	**2850**
Hoop net		4				1	9	805	1	215			2		100			**1221**
Total	**1**	**100**	**21**	**1**	**30**	**4**	**23**	**2649**	**2**	**224**	**1**	**1**	**623**	**3**	**258**	**4**	**3**	**4098**

We conducted a fall monitoring trip downstream of Pearce Ferry Rapid (October 23-26) where we set 45 baited hoop nets and angled. Of the 29 fish captured in hoop nets, ten were nonnative fish (two common carp, one mosquitofish, one fathead minnow, and six red shiner), three were flannelmouth suckers and 16 were speckled dace. Angling was relatively productive for channel catfish, with three captured within 102 minutes of effort and three within 125 minutes of effort at two different sites. We rarely capture channel catfish upstream of Pearce Ferry rapid (1 per year in 2017 and 2018). The comparatively high capture rates downstream of Pearce Ferry Rapid suggest that catfish are more abundant between Pearce Ferry Rapid and Lake Mead than upstream of Pearce Ferry Rapid, and that Pearce Ferry Rapid may be at least a partial barrier to upstream movement of channel catfish.

Asian fish tapeworm monitoring was also conducted in conjunction with fall fish monitoring efforts in the mainstem Colorado River downstream of Diamond Creek. Forty humpback chub 95-320 mm TL were held in a collapsible tank on the river bank at Bridge City (RM 239) and treated with Praziquantel at 6 mg/l for 48-hrs before being released. No Asian fish tapeworm were detected in any of the humpback chub sampled at this location.

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

Invasive aquatic species monitoring in Lees Ferry

In lieu of a spring Lees Ferry monitoring trip (as has been done in the past), we added a night of sampling to the autumn trip to improve early detection of rare, nonnative species in Glen Canyon (Project Element I.2). Thus, we now conduct our 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 specifically target areas where rare nonnatives have been caught before, and warmer areas, such as spring inflows, and sloughs/backwaters. Data collected from these efforts also 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 our rare nonnative in July of 2018, we captured 87 fish, including 66 common carp, one smallmouth bass and one brown trout. During the autumn rare nonnative monitoring trip, we captured two green sunfish, six brown trout, and only one common carp. Common carp outside of the slough were not captured during this sampling effort.

One major difference between the two sampling periods (summer vs. autumn) was the location of common carp. Typically, in July we catch a large number (between 32-208, GCMRC Grand Canyon fishes database) of common carp within the connected slough at -12 RM. We captured 66 common carp this July in the slough, while during autumn monitoring we did not catch a single common carp within the slough. The water was clear, and we saw no sign of carp in the slough in autumn. However, a large number of common carp were observed immediately downstream of Glen Canyon Dam.

Water samples to evaluate the use of eDNA technology to increase our ability to detect the presence and relative abundance of aquatic invasive species moving upstream out of Lake Mead into western Grand Canyon were not collected in FY 2018. Water samples for eDNA analysis will be collected and analyzed in FY 2019 and FY 2020 in conjunction with fish monitoring in the mainstem Colorado River downstream of Diamond Creek.

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. Predation on humpback chub by existing predators such as channel catfish and black bullhead catfish have the potential to be high, but impacts have not been quantified. The potential impact of smallmouth bass, which are not yet established in the CRe but may become established, have also not been quantified. Our goal is to evaluate the relative predation vulnerability of humpback chub to these predatory warm-water fish using methods similar to those employed for rainbow and brown trout. 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.

Summary of Progress

This year we focused on preliminary assessments of channel catfish relative abundance within the LCR. We completed a single angling trip throughout the lower 13 km of the LCR (May 21-24) and caught and tagged 32 channel catfish with an average catch per unit effort of 1 fish/hour. Channel catfish were spread throughout the lower 13 km of the LCR and typically aggregated in deeper pools with large boulders. All size classes were encountered but most of the population is dominated by large adults (Figure 1). Further effort next spring will continue to mark channel catfish so that a mark-recapture population estimate can be obtained.

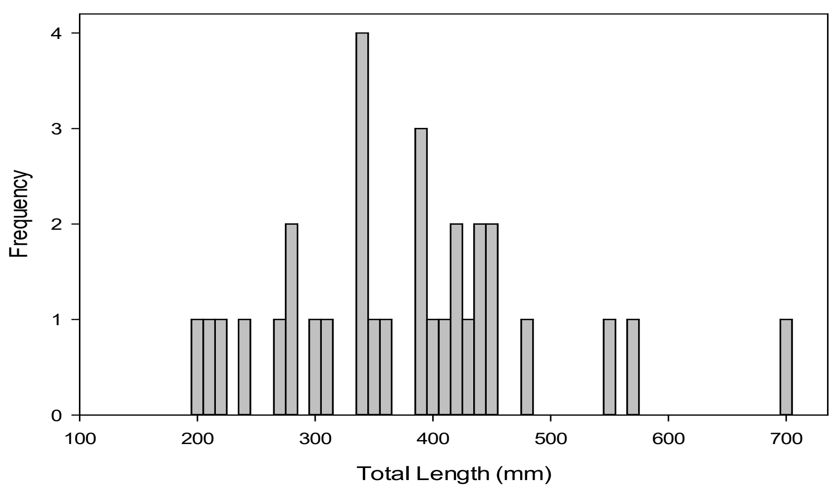

Figure 1. Length frequency histogram for 32 channel catfish angled from the Little Colorado River in 2018.

In FY 2018, laboratory evaluations of predation risk focused on assessing the potential impacts of smallmouth bass on juvenile humpback chub, bonytail chub and roundtail chub. Although smallmouth bass are not currently established in the CRe they are occasionally found in the mainstem Colorado River downstream of Glen Canyon Dam and establishment of smallmouth bass are considered a large threat to native fishes because of the damage they have caused to native fish in other areas of the Colorado River Basin. In general, smallmouth bass are at least four times as predacious as a rainbow trout under similar laboratory conditions but are approximately equivalent to brown trout in terms of predation risk for equivalent sized fish (Figure 2).

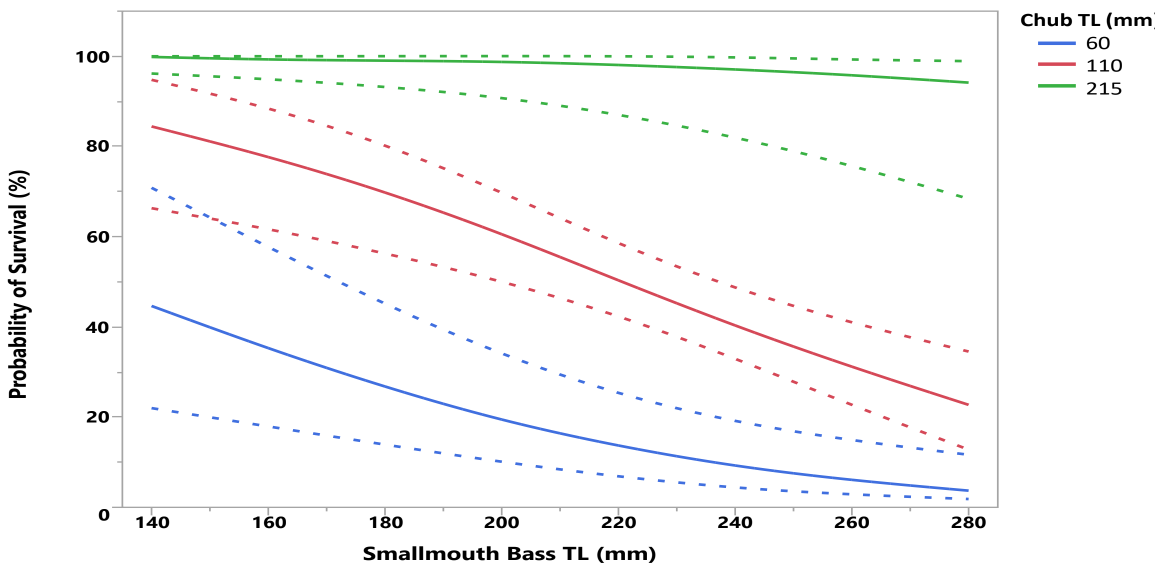

Figure 2. Percent probability that a juvenile chub 60 mm, 110 mm and 215 mm total length (TL) will survive predation by smallmouth bass in 24-hour laboratory predation trials conducted at 20 °C as bass size increases from 140 to 280 mm TL. Dashed lines represent 95% confidence intervals.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Journal Article	Are hatchery-reared rainbow trout and brown trout effective predators on juvenile native fish?		Sept 2018		Ward, D.L., Morton-Starner, R., and Vaage, B., 2018, Are hatchery-reared rainbow trout and brown trout effective predators on juvenile native fish?: North American Journal of Fisheries Management, v. 38, no. 5, p. 1105-1113, https://doi.org/10.1002/nafm.10216.
Journal Article	What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?		Sept 2018	Nov 2018	Ward D.L, and Vaage, B.M., 2018, *in press*, What environmental conditions reduce predation vulnerability for juvenile Colorado River native fishes?: Journal of Fish and Wildlife Management.
Journal Article	Key morphological features favor the success of non-native fish species under reduced turbidity conditions in the lower Colorado River Basin, USA		May 2018		Moran, C.J., Ward, D.L., and Gibb, A.C., 2018, Key morphological features favor the success of non-native fish species under reduced turbidity conditions in the lower Colorado River Basin, USA: Transactions of the American Fisheries Society, v. 147, no. 5, p. 948-958, https://doi.org/10.1002/tafs.10079.
Journal Article	Can data from disparate long-term fish monitoring programs be used to increase our understanding of regional and continental trends in large river fish assemblages?		Jan 2018		Counihan, T.D., Waite, I.R., Casper, A.F., Ward, D.L., Sauer, J.S., Irwin, E.R., Chapman, C.G., Ickes, B.S., Paukert, C.P., Kosovich, J.J., and Bayer, J.M., 2018, Can data from disparate long-term fish monitoring programs be used to increase our understanding of regional and continental trends in large river assemblages?: PLoS ONE, v. 13, no. 1 (e0191472), https://doi.org/10.1371/journal.pone.0191472.
Annual Report	Colorado River fish monitoring in Grand Canyon, Arizona—2017 Annual Report		March 14, 2018		Boyer, J.K., and Rogowski, D.L., 2018, Colorado River fish monitoring in Grand Canyon, Arizona—2017 annual report: Phoenix, Arizona Game and Fish

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
					Department, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, 45 p., https://doi.org/10.13140/RG.2.2.31954.61124.
Journal Article	Humpback Chub (*Gila cypha*) range expansion in the western Grand Canyon		March 27, 2018		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, online, https://scholarsarchive.byu.edu/wnan/vol78/iss1/4.
Journal Article	Native fish recovery in a highly regulated river		Submitted		Boyer J., and Rogowski, D.R., Native fish recovery in a highly regulated river: Submitted to Transactions of the American Fisheries Society.

Project I Budget

Project I	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$171,706	$1,500	$22,000	$231,000	$0	$37,298	**$463,504**
Actual Spent	$205,285	$1,587	$4,687	$231,000	$0	$39,842	**$482,401**
(Over)/Under Budget	**($33,579)**	**($87)**	**$17,313**	**$0**	**$0**	**($2,544)**	**($18,897)**
						FY18 Carryover	**($18,897)**

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

- Salaries were higher due to a graduate student employee shifting from part time to full time work upon graduation and higher than anticipated salary costs associated with field work.
- Operating expenses were lower than planned due to USGS paying the cost of wetlab rental space so those expenses did not come out of our project budget as we had planned.

Project J: Socioeconomic Research in the Colorado River Ecosystem

Project Lead	Lucas Bair	**Principal Investigator(s)** (PI)	Lucas Bair, USGS, GCMRC Chris Neher, University of Montana John Duffield, University of Montana Matthew Reimer, University of Alaska Michael Springborn, UC Davis Charles Yackulic, USGS, GCMRC
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SUMMARY

The overall objective of Project J is to identify preferences for, and values of, downstream resources and evaluate how preferences and values are influenced by Glen Canyon Dam 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 GCMRC. This integration will lead to the development of tools for scenario analysis that improve the ability of the GCDAMP to evaluate and prioritize management actions, monitoring, and research.

This project addresses the tribal, humpback chub, hydropower and energy, and rainbow trout LTEMP resource goals by addressing objectives with respect to the "interests and perspectives of American Indian Tribes" and to "determine the appropriate experimental framework that allows for a range of programs and actions, including ongoing and necessary research, monitoring, studies, and management actions in keeping with the adaptive management process." 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

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 and in identifying critical flaws in design and implementation methods.

In 2018 two primary tasks were undertaken: 1) further revision of the draft tribal survey instrument and associated presentation materials, and 2) permitting and approval of survey implementation on the Navajo Nation and Hualapai Tribe's reservations. Survey development continued in 2018 with Navajo Nation and Hualapai Tribe representatives and with scholars at Northern Arizona University, University of Arizona, and a Navajo cultural advisor and translator. Permitting and approval by the Navajo Nation's Human Research Review Board (Board) required presentation to and approval from the five Navajo Nation agencies over the course of 2018, in conjunction with permitting by the Navajo Nation Heritage and Cultural Preservation office and presentation to the Board. Approval by the Board was received in July 2018. Following Board approval, the PI attended chapter official and community meetings and presented information about the survey to inform chapter officials and community members of the research, receive approval and support, and schedule future focus groups. The Hualapai Tribal council granted approval of the survey in August 2018. Navajo Nation and Hualapai Tribal focus groups are scheduled in 2019. In conjunction with tribal approval and permitting, the federal survey approval process, including Fast Track approval for initial focus groups, was initiated in 2018.

In 2019 continued engagement with tribal representatives, researchers, and tribal members through focus groups and formal meetings with Navajo Nation chapters, the Hualapai Cultural Advisory Team, Hualapai cultural heritage and natural resource staff, and other tribal meetings and events will occur. Population level surveys with the Hopi Tribe, the Pueblo for Zuni, and the Southern Paiute Consortium are uncertain in 2019. Continued engagement with the Hopi Tribe and Pueblo of Zuni, learning from survey implementation with the Navajo Nation and the Hualapai Tribe, and continued survey development will potentially position the PI for population level surveys with the Hopi Tribe and Pueblo of Zuni in 2020.

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

Bair and others (2018) published a simulation 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. While informative, the Bair and others (2018) model was limiting because it imposed a predetermined structure on the shape of policy function and removal triggers were only based on rainbow trout abundance in the juvenile humpback chub monitoring reach near the LCR. In 2018, Pierce Donovan, Lucas Bair, Charles Yackulic and Michael Springborn developed a refined version of the model, using stochastic dynamic programming to identify removal actions that cost-effectively met long-term adult humpback chub abundance goals (Donovan and others, in press). The new 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 LCR 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 Bair and others (2018) 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).

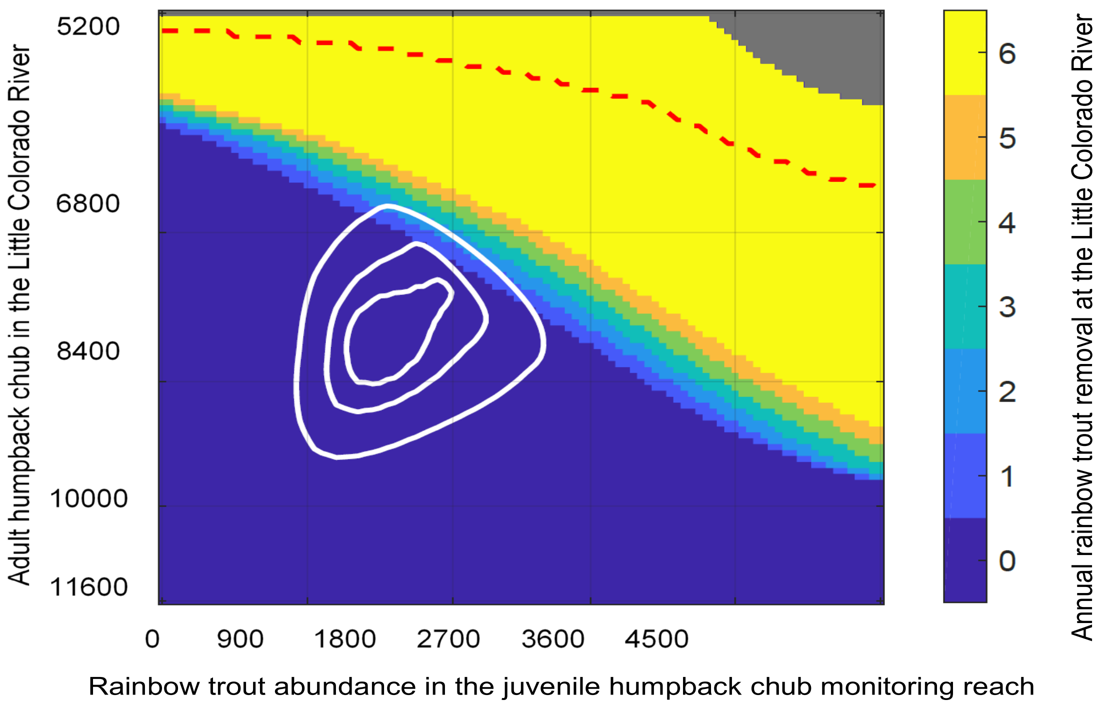

Figure 1. The policy function indicating how many mechanical removals of rainbow trout are cost-effective in a year given the current populations of rainbow trout (horizontal axis) and humpback chub (vertical axis) in the management reach. The red dashed line spanning the figure from left to right delineates where the probability of remaining above the adult humpback chub abundance goal is not certain and the grey fan-shaped region in the top right indicates rainbow trout and humpback chub abundances at which falling below the adult humpback chub abundance goal is mathematically certain over a 20-year time horizon. The concentric white curves show the likely humpback chub abundance (10%, 25%, and 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 (Figure 2). 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.

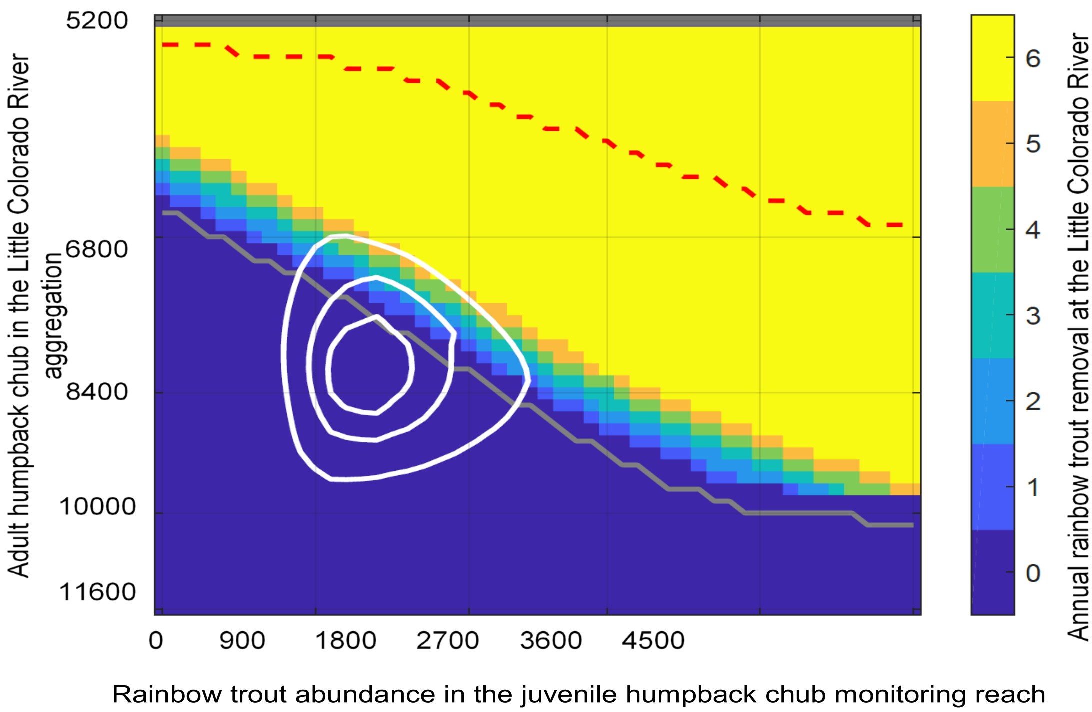

Figure 2. The policy function under uncertainty in the relationship between humpback chub survival and rainbow trout abundance for the case of the learning manager. Shading indicates how many mechanical removals of trout are optimal in a year given the current populations of trout (horizontal axis) and chub (vertical axis) in the juvenile humpback chub management reach. The red dashed line spanning the figure from left to right delineates where the probability of remaining above the adult humpback chub abundance goal is not certain. The concentric white curves show the humpback chub abundance (10%, 25%, and 50%) after 20 years under the optimal policy. The solid grey line spanning the figure from left to right (towards the bottom) shows the southern extent of abundances over which the non-learner imposes a nonzero level of control.

Lucas Bair and collaborators are expanding on the rainbow trout and humpback chub stochastic 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 (in press) 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 actions. Extending the stochastic dynamic programing model described by Donovan and others (in press) in these ways will also 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., and Bond, C.A., 2018, Enhancing native species population viability via cost-effective invasive species control in the Grand Canyon, USA: Biological Conservation, online, https://doi.org/10.1016/j.biocon.2018.01.032.

Donovan, P., Bair, L.S., Yackulic, C.B., and Springborn, M.R., *in press*, Safety in numbers—Applying chance-constrained dynamic programming to population viability analysis and adaptive management: Grand Canyon Monitoring and Research Center, FY 2018 Annual Project Report to the Glen Canyon Dam Adaptive Management Program Land Economics.

PRODUCTS/REPORTS

Type	Title	Due Date	Date Delivered	Date Expected	Citations/Comments
Publication	Testing the limits of temporal stability: Willingness to pay values among Grand Canyon whitewater boaters across decades	FY 2015-2017	Published FY 2018		Neher, C., Duffield, J., Bair, L.S., Patterson, D., and Neher, K., 2017, Testing the limits of temporal stability—Willingness to pay values among Grand Canyon whitewater boaters across decades: Water Resource Research, v. 53, no. 12, p. 10108-10120, http://dx.doi.org/10.1002/2017WR020729.
Publication	Convergent validity between willingness to pay elicitation methods: An application to Grand Canyon whitewater boaters	FY 2015-2017	Published FY 2018		Neher, C., Bair, L.S., Duffield, J., Patterson, D., and Neher, K., 2018, Convergent validity between willingness to pay elicitation methods—An application to Grand Canyon whitewater boaters: Journal of Environmental Planning and Management, online, https://doi.org/10.1080/09640568.2018.1435411.
Publication	Enhancing native species population viability via cost-effective invasive species control in the Grand Canyon, USA	FY 2015-2017	Published FY 2018		Bair, L.S., Yackulic, C.B., Springborn, M.R., Reimer, M., and Bond, C.A., 2018, Enhancing native species population viability via cost-effective invasive species

					control in the Grand Canyon, USA: Biological Conservation, online, https://doi.org/10.1016/j.biocon.2018.01.032.
Publication	Safety in numbers: Applying chance-constrained dynamic programming to population viability analysis and adaptive management	FY 2015-2017	In press FY 2018	FY 2019	Donovan, P., Bair, L.S., Yackulic, C.B., and Springborn, M.R., *in press*, Safety in numbers—Applying chance-constrained dynamic programming to population viability analysis and adaptive management: Land Economics.
Presentation	Peoples' values and objectives for river use: An example from the Colorado River in Grand Canyon		May 2018		Bair, L., 2018, Peoples' values and objectives for river use—An example from the Colorado River in Grand Canyon—presentation: Workshop on Rivers, Lands and Cultures: Learning from the Tocantins Social-ecological System, Federal University of Tocantins, Palmas, Brazil, May 15-16, 2018.
Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA		August 23, 2018		Bair, L., Reimer, M., and Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: American Fisheries Society, 148th Annual Meeting, Atlantic City, NJ, August 23, 2018, https://afs.confex.com/afs/2018/meetingapp.cgi/Paper/33683.
Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective		September 26, 2018		Bair, L., Reimer, M., and Bain, D., 2018, Socioeconomic considerations of environmental flows—Using bioeconomic

	approaches for managing invasive species in the Grand Canyon, USA				modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: DOI Economics Workshop, Washington, D.C., September 26, 2018.
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		March 2018		Springborn, M., Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: UC Davis Center for Population Biology Seminar Series, Davis, Calif., March 2018.
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		June 2018		Springborn, M., Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: Western Economics 93rd Annual Conference, Vancouver, British Columbia, Canada, June 26-30, 2018.
Presentation	Safety in numbers: Cost-effective endangered species management for viable populations		September 2018		Donovan, P., Bair, L., and Yackulic, C., 2018, Safety in numbers—Cost-effective endangered species management for viable populations—presentation: CU Environmental and Resource Economics Workshop, Vail, Colo., September 13-14, 2018.

Project J Budget

Project J	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$146,890	$3,250	$900	$107,500	$0	$26,722	**$285,262**
Actual Spent	$146,595	$10,548	$976	$62,960	$0	$26,487	**$247,566**
(Over)/Under Budget	**$295**	**($7,298)**	**($76)**	**$44,540**	**$0**	**$235**	**$37,696**
						FY18 Carryover	**$37,696**

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

- Increased travel spending due to an above average number of opportunities to present and collaborate on GCMRC science both domestically and internationally.
- Cooperative agreement spending was low because the tribal survey project (Project J.1) didn't make it through permitting and review requirements. The carryover from this Project J.1 will be spent in FY2019 on Project J.1.

Project K: Geospatial Science and Technology

Project Lead	Tom Gushue	**Principal Investigator(s)** (PI)	Thomas Gushue, USGS, GCMRC
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SUMMARY

The Geospatial Science and Technology project provides support to 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. New efforts in Amazon Webs Services-Cloud Hosting System (AWS-CHS) environment, Internet of Things (IoT) sensor transmissions, and database and front-end application development highlight the work being produced from this project. Similar to the FY 2015-2017 TWP, most work performed within this project falls within one of three main categories: Geospatial Data Analysis, Geospatial Data Management, and Access to Geospatial Data Holdings.

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 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 and 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 AWS-CHS environment, 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 in efficient, modern workflows that maintain some consistent elements and yet can be adapted to each project's unique properties.

Related to this data science initiative, this project, in conjunction with IT staff, have made available an advanced data processing server environment known as the Xen Cluster system that is configured to handle memory intensive data processing such as the development of 3D models and tools of the Colorado River corridor. The Xen Cluster allows for expanding processing power through adding additional virtual servers as needed and can be configured to allow up to ten users logged in simultaneously. The design, acquisition, configuration and deployment of this type of system is necessary for certain projects and scientists so that bottlenecks in data processing and advanced modeling techniques can be eliminated. This will allow for a monumental shift of how projects will work in the future. This project is helping to propel GCMRC forward, taking advantage of new platforms and environments, while aligning these technological advancements with the research needs of GCMRC's scientists.

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 Cloud Hosting Solutions (CHS) environment for the USGS which the Geospatial project maintains for GCMRC.
    b. The Geospatial Project also was closely involved with processing the final Glen Canyon Digital Elevation Model (DEM) representing the full channel geometry of the Colorado River corridor. Processing tasks accomplished include the removal of vegetated areas from the original Digital Surface Model (DSM) elevations collected during the 2013 overflight, masking out areas that were collected during the channel mapping field work (2014-2016), and building a final data set of continuous elevation data at 1-meter resolution for all of Glen Canyon.
2. Project C: Riparian Vegetation Monitoring
    a. The Geospatial Project designed and built a new vegetation monitoring database and application interface to assist 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 instituting a new 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 do analysis across multiple years of data (which were previously aggregated in different spreadsheet files) and more efficiently create reports on this resource in the future.

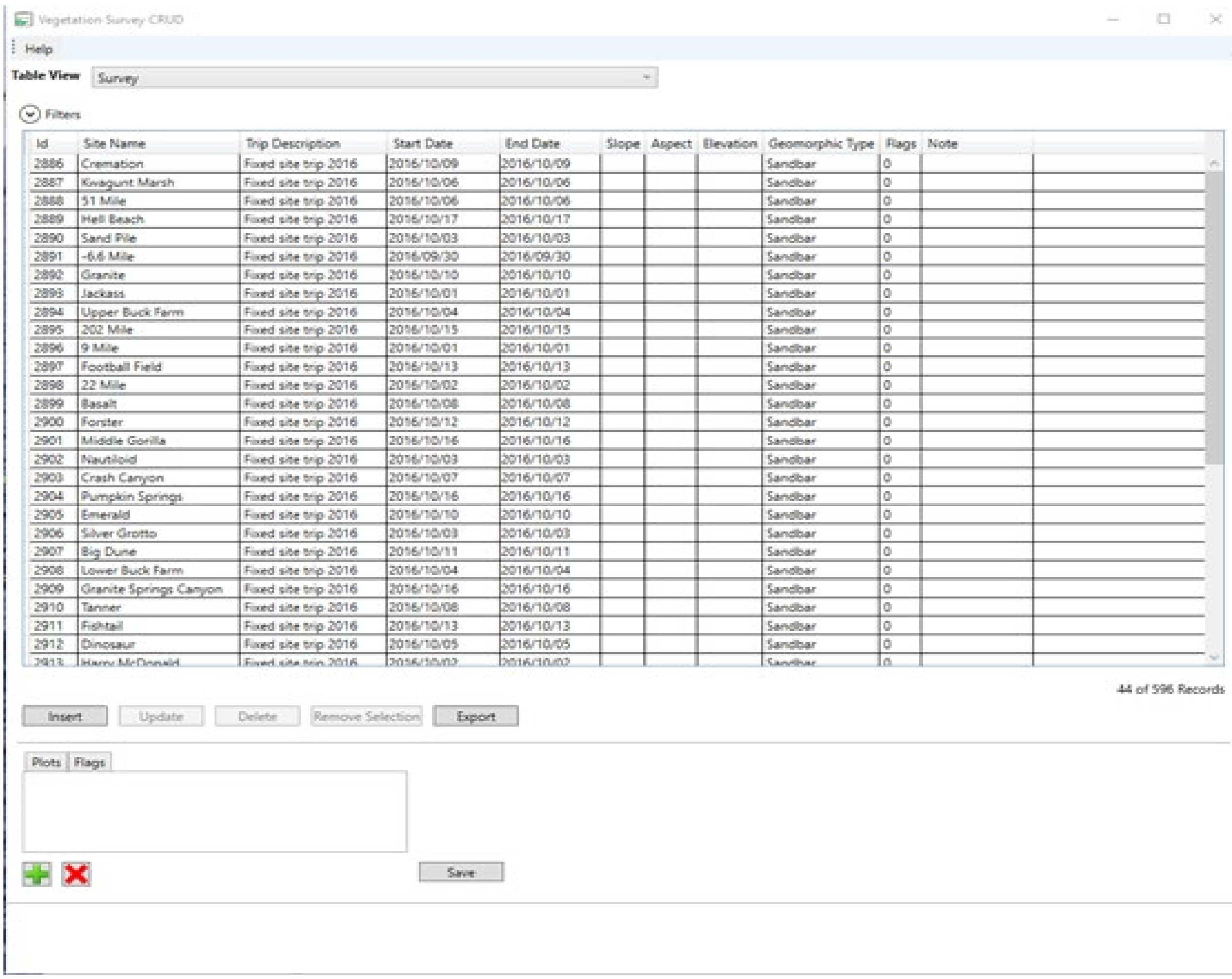

Figure 1. A sample view of the Vegetation Survey database application. Data are now stored in SQL Server with a custom application designed for data entry, querying and reporting on project-specific data.

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 and basic analysis and map production for publication and presentation purposes. The GIS project also supports some advance geospatial analysis of DEM data to determine slope characteristics of the Glen Canyon Reach.
4. Project I: Warm-Water Native and Non-Native 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 both internal systems – such as existing relational databases (Oracle, SQL Server) – and 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 the past. This included working with other USGS IT entities to resolve web-based issues and improve performance in delivering GCMRC geospatial content online.

One example of this expanded role in data management is the effort to advance GCMRC into the AWS-CHS environment. This work involved coordination at a high-level with GIS and IT staff at the USGS Southwest Biological Science Center (SBSC; GCMRC's parent organization), USGS AWS-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 to be:

Cloud Environment Goals:

1. Further develop GCMRC's capacity for working in and building applications for the Amazon cloud environment,
2. Launching the "live" sandbar database application from SBSC's Production Environment in AWS-CHS, and
3. Creating the opportunity for exploring other project-specific case-uses for AWS-CHS.

In FY 2018, we were able to achieve all three of these goals. In addition, we were also able to launch a successful pilot project that involves field transmission of data from a sensor directly to CHS-AWS via cellular and/or satellite transmission (see K.3. for more information).

Expanding Use of Source Control

This project has continued to lead GCMRC in developing and managing geoprocessing scripts, web applications and other work involving programming through online source control and versioning platforms, 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

The Geospatial project continued to perform all the administration, installation, system upgrades, and content expansion made available through the online GIS portal (Grand Canyon map portal) and increased the use of this content delivery system to a wider audience outside of internal GCMRC staff. 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.

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

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. In FY 2018, this project has led GCMRC into using AWS-CHS environment to serve data and applications online. This work involved coordination with SBSC and GCMRC science staff and the AWS-CHS team, providing direction and supervision to the lead AWS programmer on staff, and devising strategies for working within the AWS-CHS environment. We now have one complete database and application hosted in SBSC's AWS cloud environment, and one other that we have initiated the process on developing in AWS.

Perhaps the most exciting accomplishment this year has been the development of a pilot IoT Sensor project for GCMRC. The work was proof-of-concept development to determine feasibility for instituting two-way telemetry communication between scientific field equipment deployed along the Colorado River and the AWS-CHS environment. The team was responsible for determining the scope, the location, coordination with other USGS entities (including CHS, Arizona Water Science Center, outside cooperators, etc.), and upward communication to

GCMRC leadership. In just under four months, we were able to successfully demonstrate a working sensor-to-cloud two-way communication set up. This project received some seed funding from USGS to test the IoT pilot project from both GCMRC and the larger SBSC. It is important to note that this pilot project was not just new or novel to GCMRC, but to the entire USGS. Our work was presented at the inaugural USGS IoT Sensor Summit workshop held in Denver, CO in June 2018.

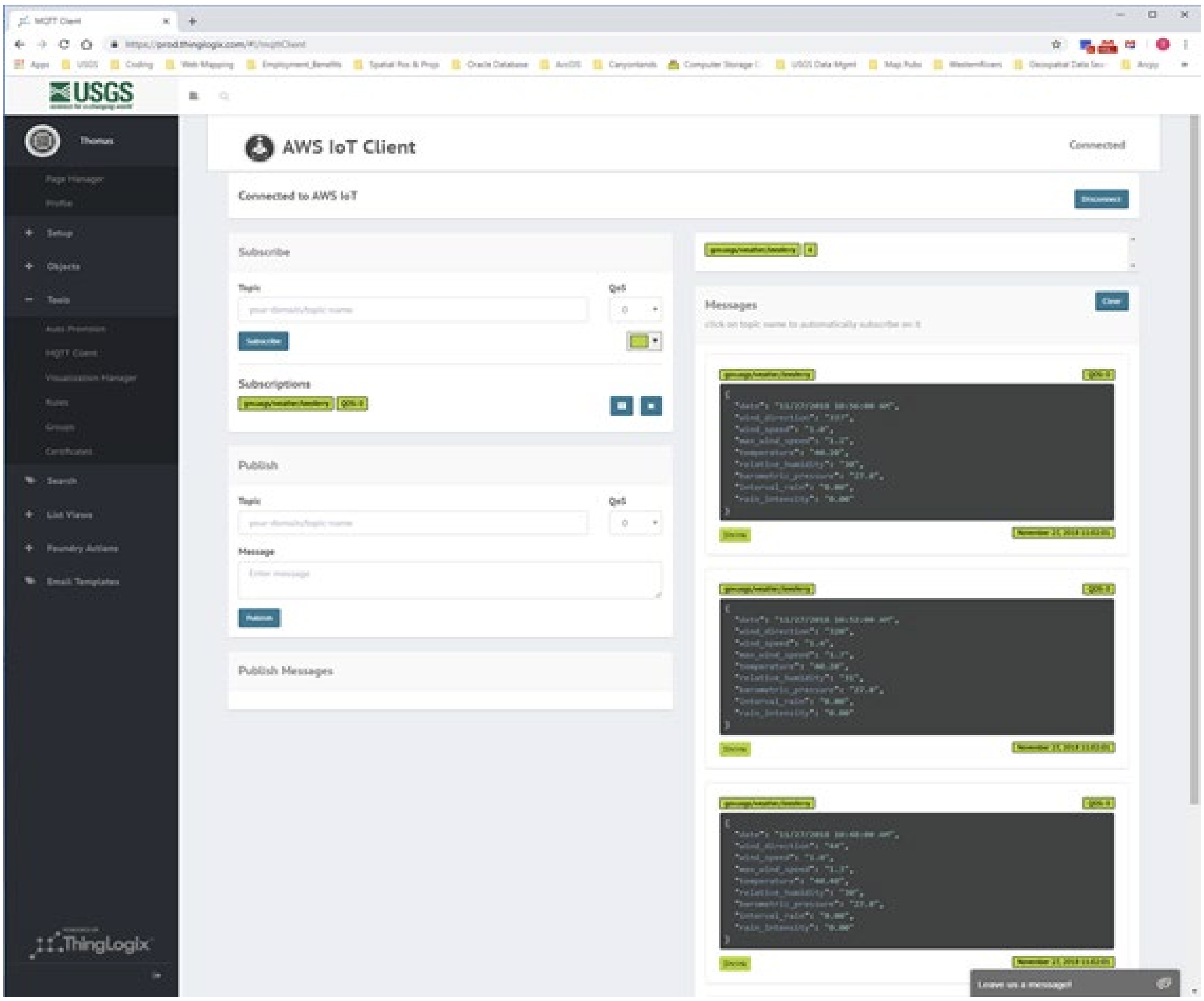

Figure 2. A screenshot of weather station data streaming to AWS IoT cloud environment for the GCMRC's Lees Ferry IoT pilot project. Data are recorded every four minutes and sent via MQTT protocol every 15 minutes.

The following is a descriptive list (with URLs) of new online mapping and data exploration applications now available through GCMRC's website.

UPDATED HFE web page: https://www.gcmrc.gov/high_flow/high_flow_default.aspx

Available through the GCMRC website, we developed a new web page that brings together online maps, data-serving web applications and relevant publications related to past HFE events.

UPDATED Sandbar time-series photo application:
https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html

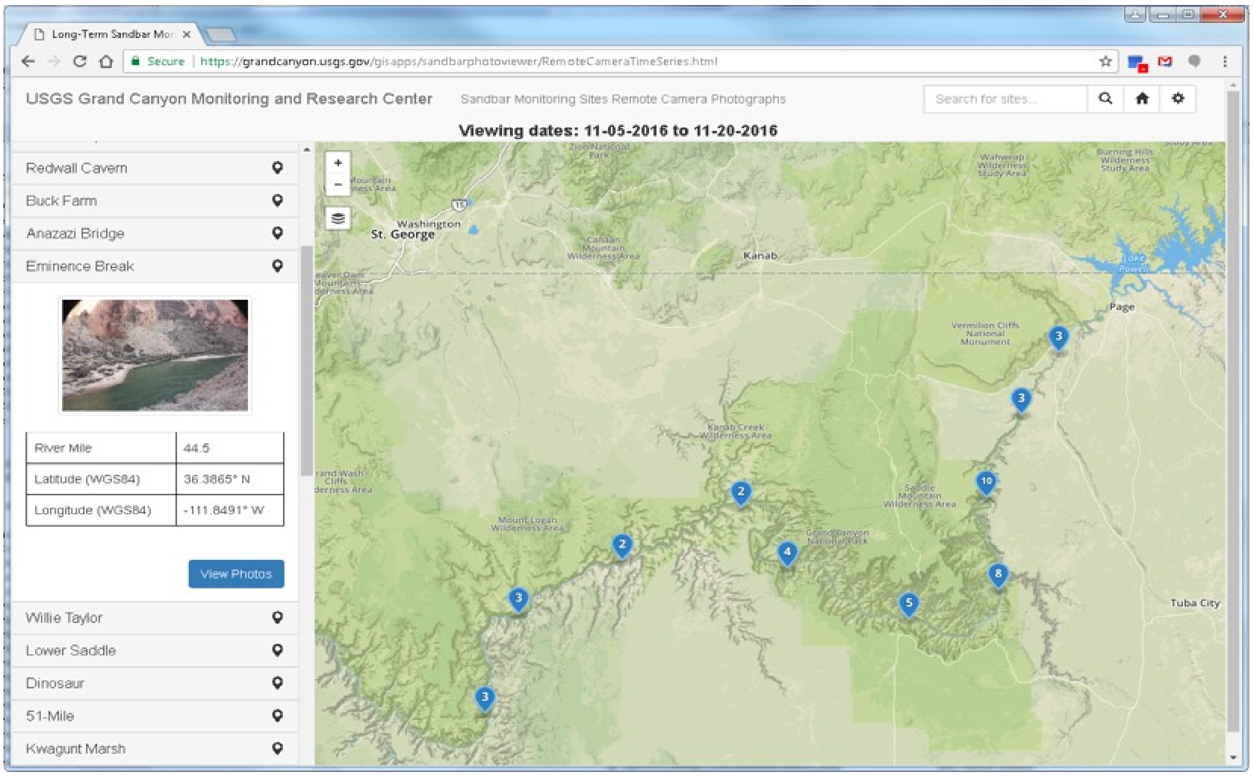

Figure 3. A view of the newly updated Sandbar photo viewer web application. Users can explore site photos through the list of sites on the left panel, or by using the interactive map.

New images from the remote camera network have been made available through the Sandbar Time-Series photo application. Under the Options Tab, pre-defined queries for the past HFEs allow a user to simply select the HFE of interest and return to viewing the sandbar photos. A custom date filtering tool also exists under Options in the application, allowing the user to specify a range of dates. This application grants access to tens of thousands of repeat photographs used to track sandbar changes and response to experimental flows along the Colorado River. Additionally, by going to the "Dual Viewer" mode, users can view repeat photos from different dates side-by-side.

UPDATED Geospatial Services page: https://www.gcmrc.gov/geospatial

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 2018 to contain Environmental Systems Research Institute (ESRI) ArcGIS 10.5.1 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 essentially 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.

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.

Because of the advances made in this project over the last few years, it became apparent that the lead in this project (GIS Coordinator) would take the initiative to begin leverage online cloud resources for delivering information to stakeholders and the public more efficiently in the future. This work has involved considerable collaboration with other IT staff in the SBSC as well as with other USGS Science Centers.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/ Comments**
Online Database and Web Application	Grand Canyon Sandbar Monitoring https://www.usgs.gov/apps/sandbar/	FY 2018	FY 2018		
Online Geodetic Control Database	https://grandcanyon.usgs.gov/gisapps /GeodeticControl (not yet available)	FY 2019		Jan 31, 2019	This database will be online in early Feb 2019.

Project K Budget

Project K	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$245,436	$4,000	$11,850	$0	$0	$40,648	**$301,934**
Actual Spent	$263,575	$2,942	$13,686	$0	$0	$43,591	**$323,795**
(Over)/Under Budget	**($18,139)**	**$1,058**	**($1,836)**	**$0**	**$0**	**($2,943)**	**($21,861)**
						FY18 Carryover	**($21,861)**

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

- Salaries were higher than anticipated due to retention of staff originally not fully budgeted in FY2018.

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
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SUMMARY

The remote sensing overflight described in Project L has been postponed and will occur no later than 2021 so that funding can be applied to other projects with greater priority. A portion of the funds for the overflight ($75,000) will be set aside in each year of the FY 2018-2020 TWP and applied to the overflight in the FY 2021-2023 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 work.

The remote sensing projects at GCMRC were subject to substantial technical staffing reductions in the FY 2018-2020 TWP due to the budget prioritization described above that led to the postponement of the next overflight. Given this and the requested expansion of the project scope, GCMRC will look to set aside more funding than initially planned in the FY 2018-2020 TWP towards the overflight. In addition, GCMRC will propose that adequate funding be allocated in the FY 2021-2023 TWP to remote sensing projects in order to rebuild technical remote sensing staffing at GCMRC to an adequate level such that data from the next overflight can be successfully processed and served in a timely manner.

Project L Budget

Project L	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$0	$0	$0	$72,816	$0	$2,184	**$75,000**
Actual Spent	$0	$0	$0	$0	$0	$0	**$0**
(Over)/Under Budget	**$0**	**$0**	**$0**	**$72,816**	**$0**	**$2,184**	**$75,000**
						FY18 Carryover	**$75,000**

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

- All funds to be carried forward as planned to cover costs of next overflight scheduled for 2021.

Project M: Administration

Project Lead	Scott VanderKooi, Chief	**Principal Investigator(s)** (PI)	Scott VanderKooi
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SUMMARY

During the Fiscal Year 2018, the budget for this project included the salaries for the communications coordinator, librarian, and 80% of a budget analyst. This budget also includes leadership personnel salaries, some travel and training for the Chief and Deputy Chief, and part of the salary of one program manager. The vehicle section covers the costs associated with Interior owned and GSA leased vehicles that 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 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 (GCY), a nonprofit organization that provides youth (ages 10-19) with educational experiences along the rivers and canyons of the southwest, including the Grand Canyon. GCMRC scientists participated in the two Partners in Science river trips conducted in FY 2018 during which they educated youth participants in Colorado River science and directed them in data collection efforts in support of the FY 2018-2020 TWP. 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 fishes including the humpback chub (Projects G and I), as well as rainbow trout and other nonnative fishes (Projects H and I).

Project M Budget

Project M	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$618,824	$40,000	$233,000	$0	$0	$138,741	**$1,030,565**
Actual Spent	$544,493	$16,343	$158,272	$0	$0	$111,872	**$830,980**
(Over)/Under Budget	**$74,331**	**$23,657**	**$74,728**	**$0**	**$0**	**$26,869**	**$199,585**
						FY18 Carryover	**$199,585**

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

- Salary surplus due to USGS providing some funding for GCMRC leadership salaries in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2019 funding.
- Travel & Training surplus due to reduced travel and USGS providing some funding for GCMRC leadership travel and training all in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2019 funding.
- Operating Expenses surplus due to reduced spending on equipment and supplies (including IT) in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2019 funding.

Logistics Budget

Logistics	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$284,226	$5,000	$880,543	$10,000	$0	$182,281	**$1,362,050**
Actual Spent	$283,504	$410	$895,000	$0	$0	$183,404	**$1,362,318**
(Over)/Under Budget	**$722**	**$4,590**	**($14,457)**	**$10,000**	**$0**	**($1,123)**	**($268)**
						FY18 Carryover	**($268)**

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

- Training expenses decreased due to delay in hiring new Logistics Coordinator.
- Operating expenses increased due to higher than expected costs for supplies and materials in support of field work.

Project N: Hydropower Monitoring and Research

Project Lead	Lucas Bair	**Principal Investigator(s)** (PI)	Lucas Bair
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SUMMARY

The overall objective of Project N is to identify, coordinate, and collaborate on monitoring and research opportunities associated with operational experiments at GCD to meet hydropower and energy resource objectives, as stated in the LTEMP ROD. Operational experiments include experiments proposed in the LTEMP EIS (e.g., HFEs, 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 remaining consistent with long-term sustainability of other downstream resources.

Project N: 14.1. Hydropower Monitoring and Research

In 2018, Lucas Bair collaborated with researchers at Northern Arizona University to identify the impact of 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 Northern Arizona University (Bain and Aker, 2017). This collaboration will provide foundational research to meet the objective of Project N and will attempt to estimate and minimize impacts of proposed experiments on hydropower as part of the experimental design. To minimize impacts to hydropower and energy resources, modeling is being used to estimate the total economic value of hydropower generated at Glen Canyon Dam. The total value of hydropower generated at Glen Canyon Dam includes cost associated with energy generation, greenhouse gas emissions, human health, and other regional impacts. These impacts are dependent on the price of natural gas and the integration of additional generation, including renewable energy, into the electricity sector. Scenarios incorporating these factors into power system modeling will be used to assess total economic costs associated with experimental flows at Glen Canyon Dam. This research is being coordinated with the evaluation of hydropower costs associated with trout management flows in Project J.2.

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.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Conference Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA		August 23, 2018		Bair, L., M. Reimer, D. Bain, 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: American Fisheries Society, 148th Annual Meeting, Atlantic City, NJ, August 19-23, 2018.
Conference Presentation	Socioeconomic considerations of environmental flows: Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA		September 26, 2018		Bair, L., M. Reimer, D. Bain, 2018, Socioeconomic considerations of environmental flows—Using bioeconomic modeling to identify cost-effective approaches for managing invasive species in the Grand Canyon, USA—presentation: DOI Economics Workshop, Washington, D.C., September 2018.

Project N Budget

Project N	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$9,296	$750	$300	$0	$0	$1,610	**$11,956**
Actual Spent	$9,753	$0	$0	$0	$0	$1,517	**$11,270**
(Over)/Under Budget	**($456)**	**$750**	**$300**	**$0**	**$0**	**$93**	**$687**
						FY18 Carryover	**$687**

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

- N/A

Appendix 1: Lake Powell Water Quality Monitoring

Program Manager (PM)	Bridget Deemer	**Principal Investigator(s)** (PI)	Bridget Deemer, USGS, GCMRC Nick Voichick, USGS, GCMRC
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Telephone	928-556-7316		

SUMMARY

In FY 2018, the GCMRC collected physical, biological, and chemical data and samples from Lake Powell, Glen Canyon Dam (GCD), and Lees Ferry. GCMRC also archived collected data in an existing Microsoft Access database as well as engaging in preliminary database QA/QC activities. A new interagency agreement was signed in FY 2018, supporting GCMRC involvement in the Lake Powell Water Quality Monitoring program over the next year with the potential for funding for up to five years. In early FY 2018, GCMRC convened a protocol evaluation panel comprised of scientists with relevant expertise to conduct an independent review of the Lake Powell Water Quality Monitoring Program and evaluate the water-quality work of the GCMRC in Lake Powell. This review was funded in the FY 2015-2017 TWP.

Project Summary

GCMRC has conducted a long-term water-quality monitoring program of Lake Powell and GCD releases in collaboration with Reclamation and 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 downstream of 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 2018, Reclamation conducted five complete reservoir-wide surveys with involvement from GCMRC (Table 1). In addition, GCMRC conducted six complete forebay surveys and four partial surveys of the GCD draft tubes and Lees Ferry to supplement the quarterly surveys (Table 1). November 2017 was the only month in FY 2018 with no measurements taken owing to yearly 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 of laboratory analyses of these samples are usually received within two months of collection. These data are all entered into a Microsoft Access database. Progress continues to be made to serve data from this database on the GCMRC website. Reclamation also uses a subset of the water quality data to run the CE-QUAL-W2 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. 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 2018.

Date	Sampling Activity
10/26/17	Quarterly survey
12/12/17	Forebay, draft tubes, and Lees Ferry
01/18/18	Draft tubes and Lees Ferry
01/26/18	Quarterly survey minus draft tubes and Lees Ferry
02/06/18	Forebay, draft tubes, and Lees Ferry
03/22/18	Quarterly survey
04/23/18	Forebay, draft tubes, and Lees Ferry
05/14/18	Forebay, draft tubes, and Lees Ferry
06/05/18	Quarterly survey
07/02/18	Forebay, draft tubes, and Lees Ferry
8/07/2018	Forebay, draft tubes, and Lees Ferry
9/10/2018	Quarterly survey

Analysis Activities

Historical nutrient data from the Lake Powell Water Quality Monitoring program are being used together with data from the three major gaged tributary sites to Lake Powell (USGS stream gages 09180500, 09315000, and 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 SRP concentrations was conducted in March of 2018. Currently, all nutrient and major ion analyses are done by Reclamation's Lower Colorado Region Water and Soil Laboratory in Boulder City, Nevada. This lab was compared to the High Sierra Water Laboratory 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 Reclamation lab. Similarly, water column total phosphorus concentrations reported by High Sierra were, on average, 52% of the values reported by Reclamation. Samples were well above reported detection limits (at least three times 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 High Sierra Laboratory that specializes in phosphorus measurements. Currently, funding to send duplicate samples for phosphorus measurements is beyond the program budget as a full suite of phosphorus analytes would cost $75 per sample at High Sierra Laboratory.

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) is being used together with data from this monitoring program to examine patterns in salinity transport within the basin. Initial results suggest that Lake Powell acts as a sink for total dissolved solids and functions to moderate downstream salt concentrations.

Protocol Evaluation Panel

A protocol evaluation panel was convened from October 24-26, 2017 in Page, AZ. The purpose of this water-quality review was to satisfy requirements under the GCDAMP that the science work of the GCMRC receive periodic independent review. Some important questions that were addressed by the review included: 1) what is the status of water quality in Lake Powell and the Colorado River downstream of the GCD and how does it vary over time, 2) how might water quality in Lake Powell and the Colorado River downstream of the GCD change in the future, and 3) how might management of the GCD affect water quality in Lake Powell and the Colorado River downstream of the GCD both now and in the future.

The panel consisted of five scientists, Dr. Kristin Strock (Dickinson College), Dr. Edward Stets (U.S. Geological Survey), Dr. Stephen Hamilton (Michigan State University and the Cary Institute of

Ecosystem Studies), Dr. Todd Tietjen (Southern Nevada Water Authority), and Dr. Chris Holdren (Environmental Consultant). The panelists were asked to focus on four main questions which were developed with input from GCMRC, Reclamation, and NPS. The questions and answers are summarized on the GCDAMP wiki: (http://gcdamp.com/index.php?title=2017_Water_Quality_PEP) and a copy of the final report can be found here: https://www.usbr.gov/uc/rm/amp/twg/mtgs/18jun25/Attach_07d.pdf.

In brief, the panel suggested five main priorities for the Lake Powell monitoring program (Table 2). Per these recommendations, several more highly resolved vertical water chemistry profiles were also conducted during FY 2018. Sampling 10 m above and 10 m below the penstock demonstrates that biologically available phosphorus can vary significantly near the depth of the penstock, at least during some periods of year. Given that the cone of influence for penstock water withdrawals is estimated to be about 30 m thick (Bureau of Reclamation, 2011), continued sampling above and below the thermocline can provide better insight into both the water column structure in the reservoir and the chemistry of water being released downstream. We have also improved our current sensor calibration practices with Seabird Electronics and have updated our protocols for both sensor storage and pH sensor calibration since pH appears to be the most sensitive to drift. Funding is available through the new Interagency Agreement for GCMRC IT specialists to work with GCMRC limnologists towards improving data management and data serving capacities. In addition, a GCMRC postdoctoral scientist is working to analyze existing data and is pursuing various avenues to encourage use of this data by outside groups.

Table 2. Priorities identified by the FY 2018 Protocol Evaluation Panel.

Priorities
• Improve data management including metadata.
• Analyze existing data to reveal trends and inform future monitoring.
• Increase vertical sampling resolution of the reservoir water column at key sites.
• Use the results of modeling experiments and analysis of previous data to consider reducing the spatial extent (number of sites) during quarterly sampling.
• Implement more detailed and formalized sensor calibration and QA/QC of field and lab procedures.

Current Conditions

Hydrology

Lake Powell received 4.6 million-acre feet (maf, 43% of the 1981-2010 average) of unregulated inflow in water year (WY) 2018, less than the inflow observed in 2016 or 2017 (89% and 110% of average, respectively). The peak reservoir elevation in WY 2018 was 3628.4 feet on October 1, 2017, compared to a July peak of 3635.8 feet in WY 2017. At the end of WY 2018, Lake Powell's surface elevation was 3592.3 ft with storage of 11 maf, or 45% of full capacity. This is down from the end of WY 2017 when surface elevation was 3,628.4 feet, and storage was 14.7 maf.

Releases for WY 2018 totaled 9.0 maf (the same as for WY 2016 and WY 2017) with operations under the Upper-Elevation Balancing Tier. Operations for WY 2019 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

Despite relatively low reservoir elevation by the end of WY 2018, Glen Canyon Dam release temperatures did not reach the highs that they have reached during other recent years. Peak GCD release temperatures as of early October 2018 were only 12.1°C. This is notable given that peak temperatures in GCD releases have exceeded 15°C in 2 of the 5 previous years.

Lake Powell Limnology

Similar to other years, an interflow plume of low dissolved oxygen (DO) water moved through Lake Powell and contributed to low (but not historically low) values of DO in the GCD tailwaters (minimum DO of 6.6 mg/L in October of 2018, compared to 4.4 mg/L in October 2014). The NPS continues to track and monitor the quagga mussel population throughout Lake Powell. In the past few years, the lake has been experiencing lower than average water levels revealing adult mussels attached to canyon walls and other surfaces that were not previously visible.

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). 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 over the next two years 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.

Vernieu, W.S., 2015a, 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., http://dx.doi.org/10.3133/ds959.

Vernieu, W.S., 2015b, 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., http://dx.doi.org/10.3133/ds471.

PRODUCTS/REPORTS					
Type	**Title**	**Due Date**	**Date Delivered**	**Date Expected**	**Citations/Comments**
Journal articles and other major pubs.	Lake Powell reduces alkalinity and total dissolved solid loads to the Lower Colorado River Basin			Fall 2019	Planned submission to the peer-reviewed journal *Limnology and Oceanography* in February 2019.
Abstracts presented at professional meetings			June 12, 2018		Deemer, B.R., E. Stets, and C.B. Yackulic, 2018, Lake Powell significantly reduces the concentration, seasonal variation, and downstream transport of major cations and anions in the Colorado River: Talk at the Association for the Sciences of Limnology and Oceanography Meeting, Victoria, B.C.

Lake Powell Budget (Not GCDAMP funded)

Lake Powell (NOT GCDAMP funded)							
	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 23.619%	Total
Budgeted Amount	$126,627	$5,899	$55,307	$0	$0	$44,364	**$232,197**
Actual Spent	$75,291	$5,899	$9,512	$0	$0	$21,423	**$112,125**
(Over)/Under Budget	**$51,336**	**$0**	**$45,795**	**$0**	**$0**	**$22,941**	**$120,072**
FY17 Carryover	$32,999					FY18 Carryover	$120,072

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

- This project is funded entirely by Reclamation from **non-GCDAMP** funding.
- A new 5-year agreement was signed in in late FY2018 with the majority of this funding carried forward to FY2019.

Carryover Budget from Previous Fiscal Years

Carryover from Previous Fiscal Years	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$89,000	$5,000	$165,300	$0	$20,000	$40,339	**$319,639**
Actual Spent	$29,555	$4,965	$15,316	$0	$20,000	$7,753	**$77,589**
(Over)/Under Budget	**$59,445**	**$35**	**$149,984**	**$0**	**$0**	**$32,586**	**$242,050**
						FY18 Carryover	**$242,050**

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

- Surpluses due to delayed hiring and spending on equipment and supplies in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2019 funding.

Budget Summary—AMP Total (without Lake Powell Agreement)

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

Total	Salaries	Travel & Training	Operating Expenses	Cooperative Agreements	To other USGS Centers	Burden 15.557%	Total
Budgeted Amount	$4,430,908	$120,585	$1,659,399	$1,685,944	$430,809	$1,016,807	**$9,344,452**
Actual Spent	$4,263,134	$80,115	$1,393,109	$1,501,871	$458,620	$937,462	**$8,634,312**
(Over)/Under Budget	**$167,774**	**$40,470**	**$266,290**	**$184,073**	**($27,811)**	**$79,345**	**$710,140**
Experimental Funds (Project F)							**$88,000**
						FY18 Carryover	**$798,140**

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

- Surpluses due in part to reduced spending in all categories in an effort to maximize carryover of GCDAMP funds due to uncertainty about FY2019 funding.
- FY2018 carryover includes $88,000 from the experimental fund to support increased work associated with the 2018 Bug Flows Experiment as well as $174,508 in planned carryover to FY2019 as identified in the FY2018-20 Triennial Workplan and $75,000 in planned carryover to support the 2021 overflight.